Neutrino Oscillations

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the American Physical Society (APS)

BROOKHAVEN
NATIONAL LABORATORY

Outline

- **Brief review of natural and manmade sources and detectors.**

- **Current status of data from oscillations with emphasis on the recent measurement of θ_{13}**

- **Benefits of θ_{13} and the scientific case for a new accelerator experiment.**

- **Reference: The recent review of Long-Baseline for annual reviews (2016) by Diwan, Galymov, Qian, Rubbia**

  http://www.phy.bnl.gov/~diwan/talks/Brazil

I will move from basic to technical explanation in the talk.

What are neutrinos ?

$$n \rightarrow p \ e^- \ \bar{\nu}_e$$

- **A particle with no electric charge. Predicted in 1930 by Pauli, and detected in 1957 by Reines and Cowan.**

- **It is emitted in radioactive decay. And has no other types of interactions.**

- **It has 1/2 unit of spin, and therefore is classified as a Fermion (or particle of matter.)**

- **Neutrino is extremely light.**

- **Neutrino comes in flavors !**

- **Neutrino is left handed ! Or has no mirror image !**

- **Neutrinos are as numerous as photons in the Universe.**

- **Important component of dark matter. May be responsible for matter/antimatter asym.**
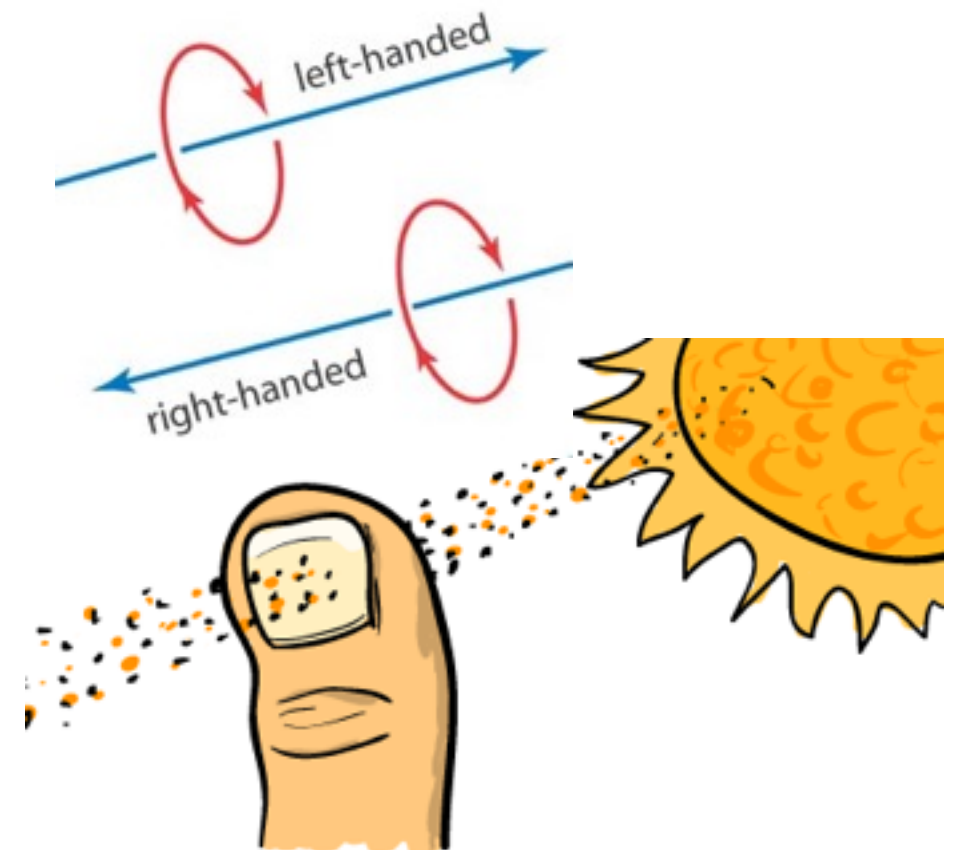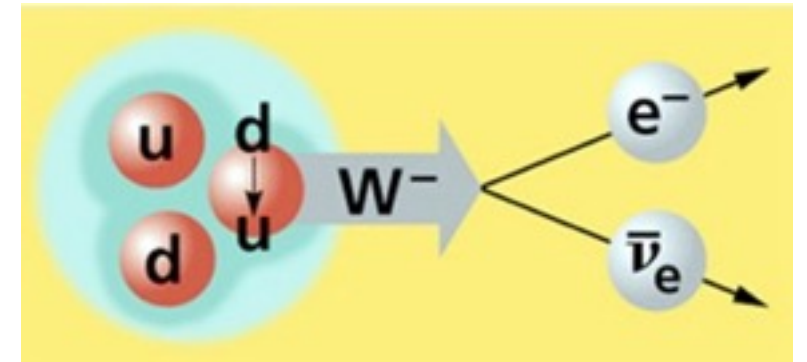
From the Sun:
10^{11} neutrinos/cm^2/sec

What do we know and how do we know it ?

● **Neutrinos are definitely massive with extremely small mass - from the existence of oscillations.**

● **Neutrino is the most abundant particle of matter with probably only 3 active types - cosmology and precision EW.**

● **Neutrino mass and mixing is completely different compared to quarks. I will review backwards for simplicity.**

fermion masses
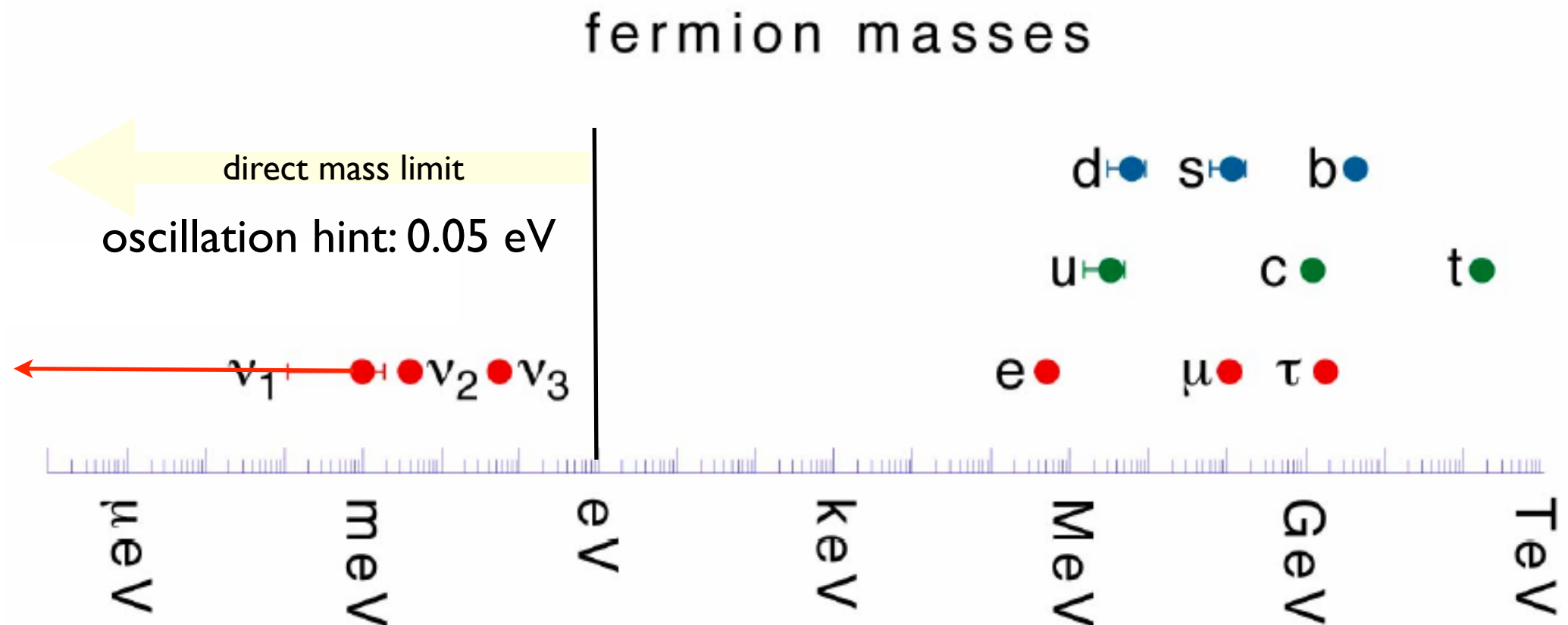
Neutrino Detection

Recoil particles
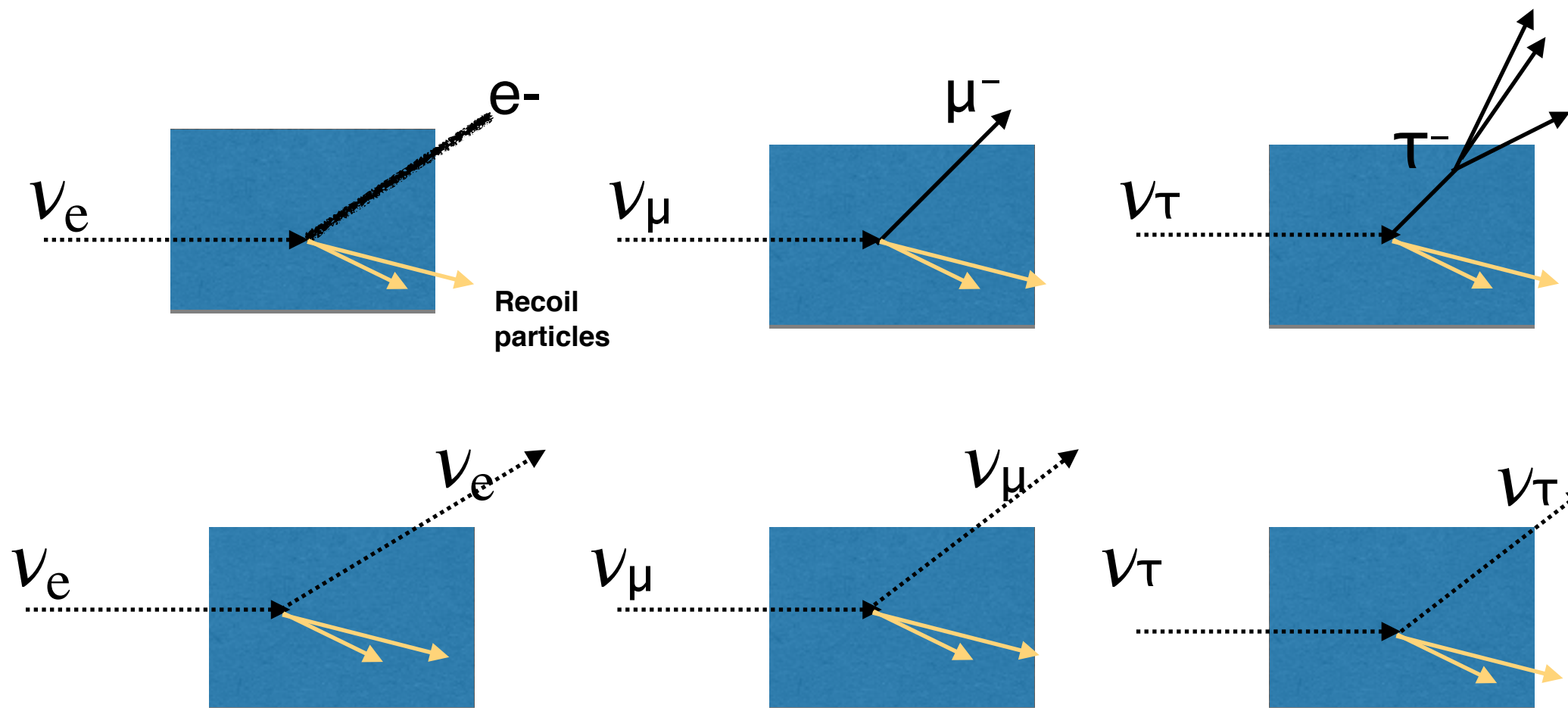
- The neutrino has no charge and so it is invisible as it enters a detector. Only very rarely it interacts and leaves charged particles that can be detected.

- Neutrino collision on atoms in detectors produces a charged lepton. (Charged Current)

- The electron, muon, tau have very different signatures in a detector.

- Neutrino can also collide and scatter away leaving observable energy.(Neutral Current)

How to detect, how many events ?

- Events = Flux (/cm^2/sec)*Cross-section(cm^2)*Targets

- Targets are the number of particle targets in a detector. Detector itself serves as the target for interactions.

- 1 ton of water ~ 6 x 10^{29} protons and neutrons and ~3x10^{29} electrons

- Practical experiments will have efficiency as a function of energy.

- Typical cross section is 10^{-38} cm^2 x Energy (GeV)

- Neutrinos from various sources have huge energy range: eV to 10^{15} eV.

- Cross sections for low energies can be extremely small.

What is the scientific interest in neutrinos ?

| FERMIONS | matter constituents spin = 1/2, 3/2, 5/2, … | | | | | |

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times 10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-0.13)\times 10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times 10^{-9}$	0
τ tau	1.777	−1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

•~20 yrs ago all neutrino masses were thought to be 0 and all neutrino flavors distinct.

•With new discoveries a distinct, unexpected pattern appears to be emerging.

•Science of neutrinos is has deep connections to understanding of matter, cosmology, and astrophysics.

• Existence of neutrino mass itself is physics beyond the standard model because in the standard model there is no interaction with right handed neutrinos. And so by definition the mass is zero.

•A new mechanism for mass generation may be needed in which neutrinos are their own anti-particles.

Natural Neutrino Sources on Earth's

- **The Sun**

  - **<0.5 MeV, 10^{11} /cm^2 s**

  - **3-14 MeV, 3×10^6 /cm^2 s**
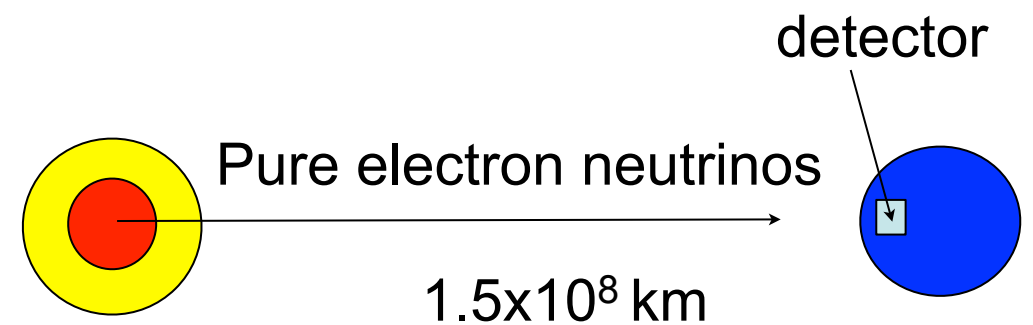
- **Cosmic rays hitting Atmosphere**

  - **~1 GeV, ~4000/m^2/sec**

- **Radioactive decays in the Earth**
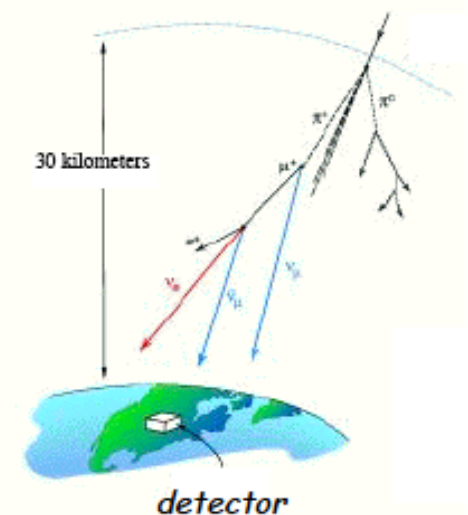
  - **<3 MeV, 10^6-10^7 /cm^2/sec**

- **Supernova. 99% of the energy of the explosion goes into neutrinos of all types. ~10 MeV, 20 seen in 1987.**

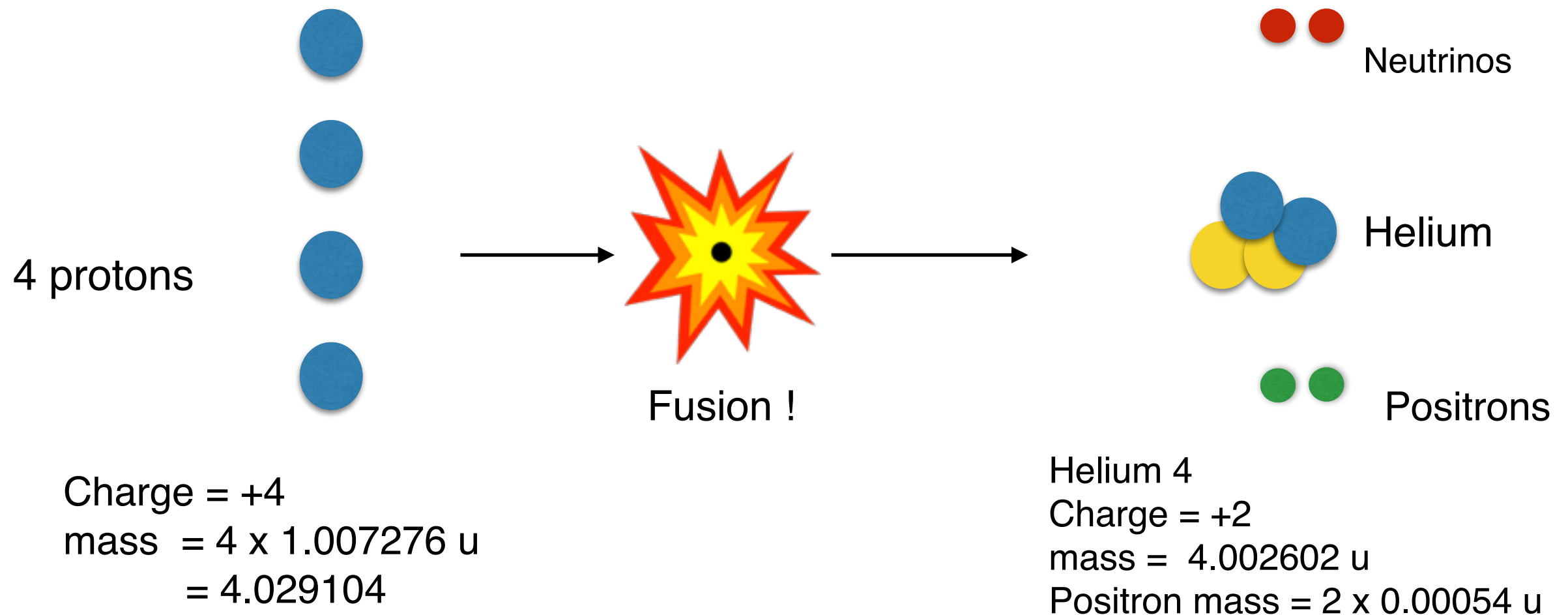- **CMB nus. 300 cm^{-3} @ 2.7 K. (not detectable as yet).**

- **Very high energy sources from deep space.**

detector

Pure electron neutrinos

1.5×10^8 km
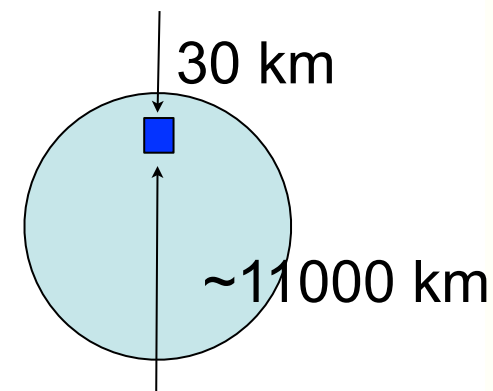
mix of muon and electron types

30 km

~11000 km

30 kilometers

detector

The Sun

4 protons

Neutrinos

Fusion !

Helium

Positrons

Charge = +4
mass = 4 x 1.007276 u
         = 4.029104

Helium 4
Charge = +2
mass = 4.002602 u
Positron mass = 2 x 0.00054 u

Energy released = 0.02542 u = 23.68 MeV/c^2 ~ 3.8 x 10^{-12} Joules

4 Hydrogen nuclei (protons) fuse into a Helium4 nucleus and release energy and neutrinos. Total energy from Sun is 3.8 x 10^{26} Watts !
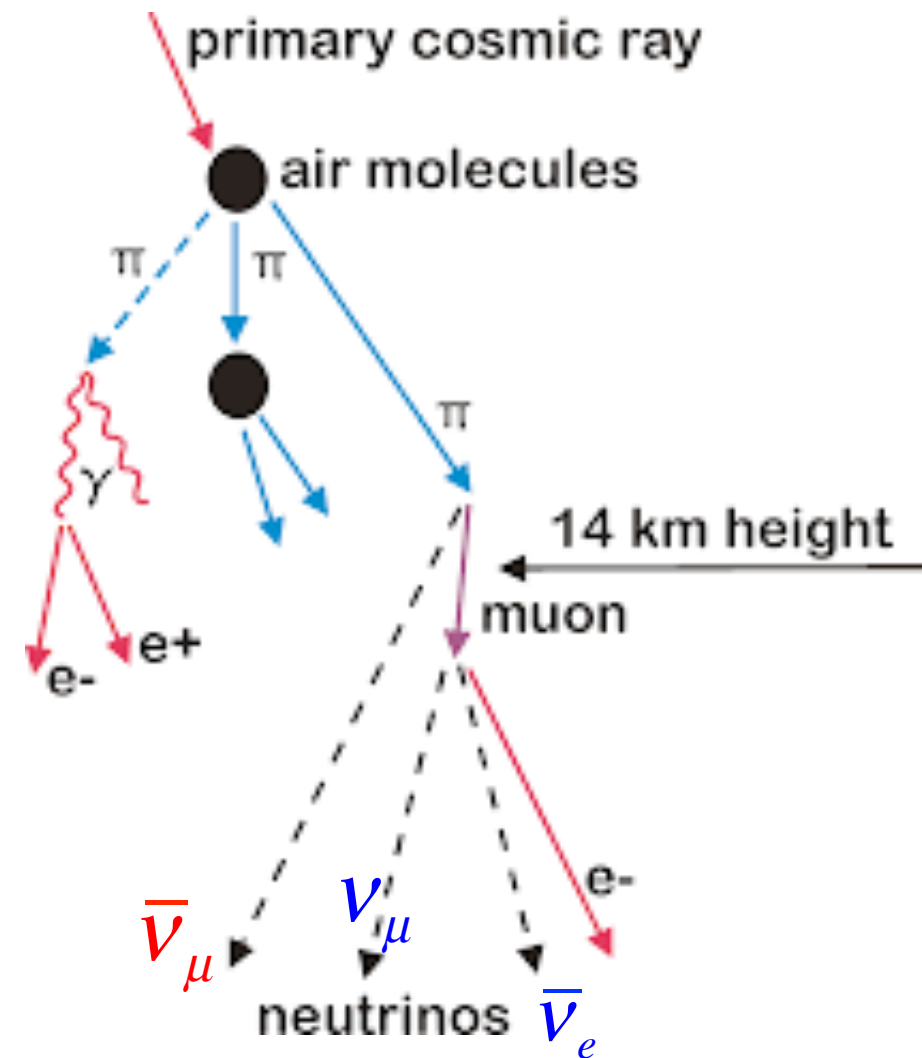
=> 680 million tons of hydrogen burns each second ! How many neutrinos are produced each second ?
There are many other channels of solar neutrinos and so the spectrum is quite complicated and goes up to ~15 MeV. (Standard Solar model)

Cosmic Rays

Altitude (km)

For Energy > 1 GeV

$\nu_\mu + \bar{\nu}_\mu$

$\mu^+ + \mu^-$

$p + n$

$e^+ + e^-$

$\pi^+ + \pi^-$

Measurements of negative muons

Vertical flux $[m^{-2} s^{-1} sr^{-1}]$

Atmospheric depth $[g\ cm^{-2}]$

From PDG 2015

primary cosmic ray

air molecules

π π π

γ

14 km height

muon

e-   e+   e-
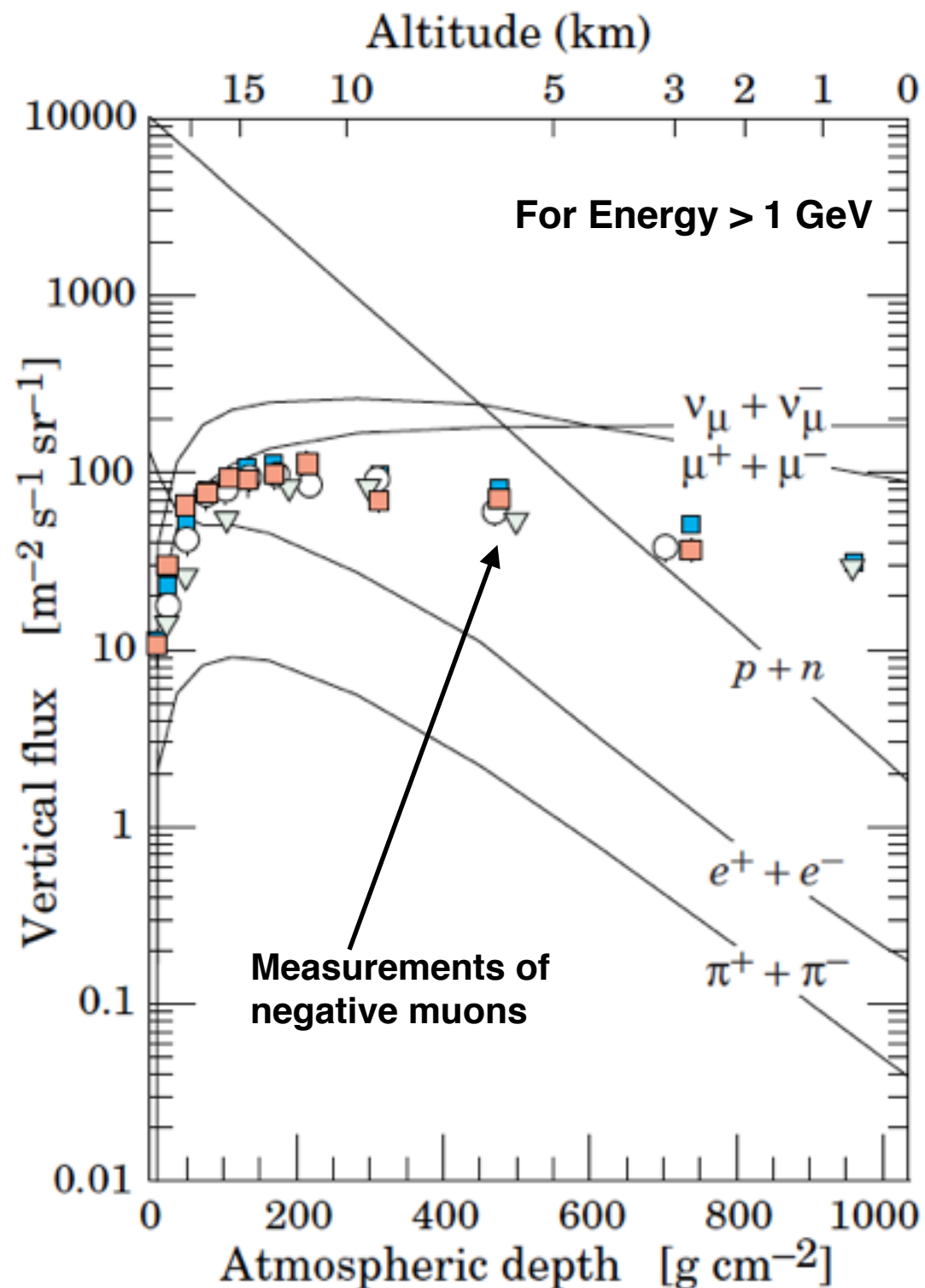
$\bar{\nu}_\mu$ ν_μ neutrinos $\bar{\nu}_e$

There should be 3 neutrinos for each muon.

Ratio of neutrinos (e-type/mu-type) = 1/2

From high altitude muon data one can roughly calculate neutrino flux ~ 4000 /m²/sec

Neutrinos from the sky
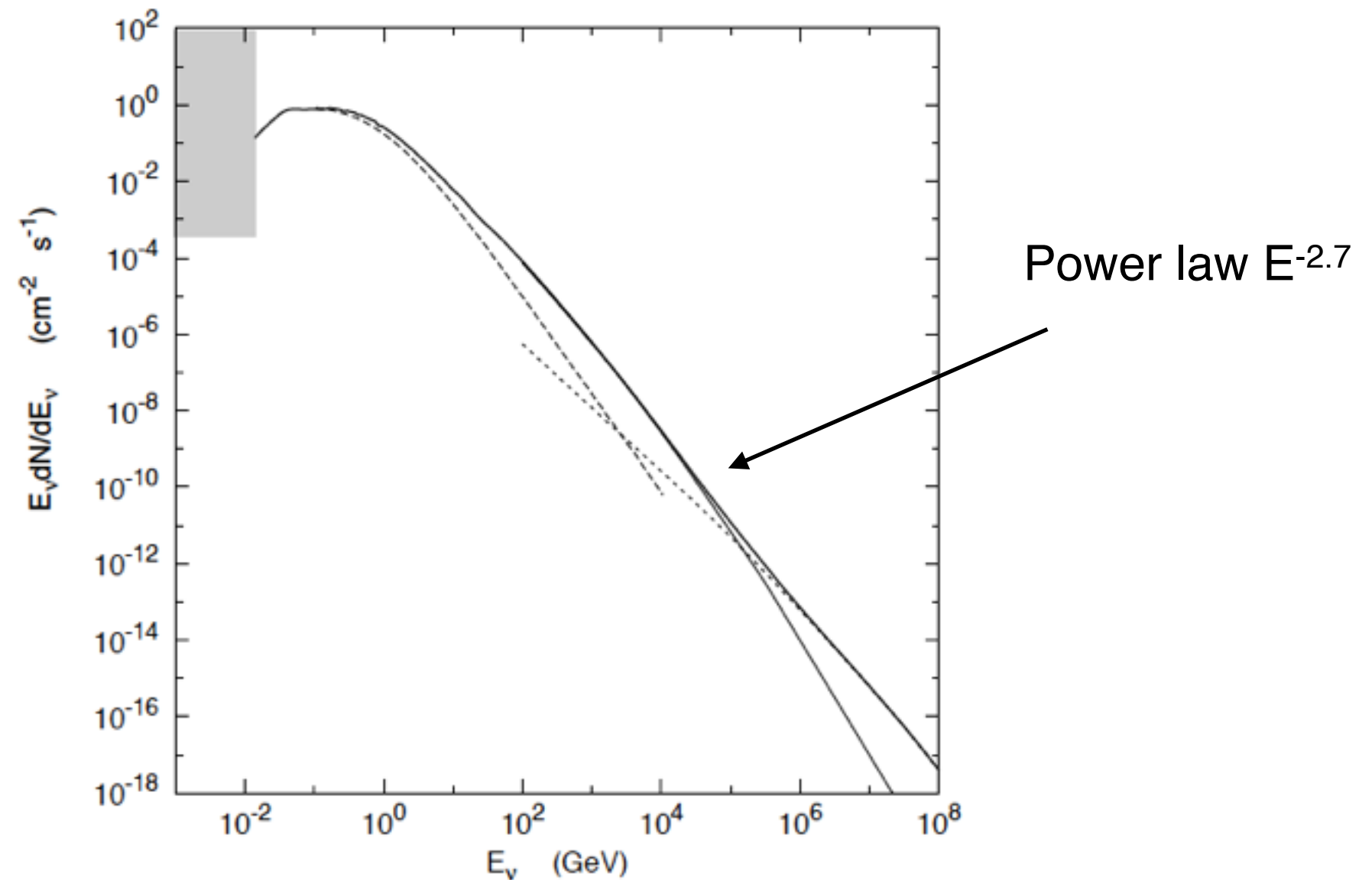
Figure 25 Global view of the neutrino spectrum: vertical flux of $\nu_\mu + \bar{\nu}_\mu$ (heavy solid line); $\nu_e + \bar{\nu}_e$ (dashed line); prompt neutrinos (dotted line); $\nu_\mu + \bar{\nu}$ from pions and kaons (thin solid line at high energy). The shaded region is dominated by solar neutrinos.

Power law E$^{-2.7}$

From Gaisser and Honda (2002)

Human-made Neutrino Sources

Pure electron anti-neutrino source. Isotropic (4Pi) beam.

- **Nuclear reactors.**

  - **<10 MeV, 6×10^{20} /3GW(th)**

- **Accelerator Beam (10-120 GeV proton)**

  - **1-100 GeV, $10^{17}/m^2/GeV/MW*yr$ @1 km.**
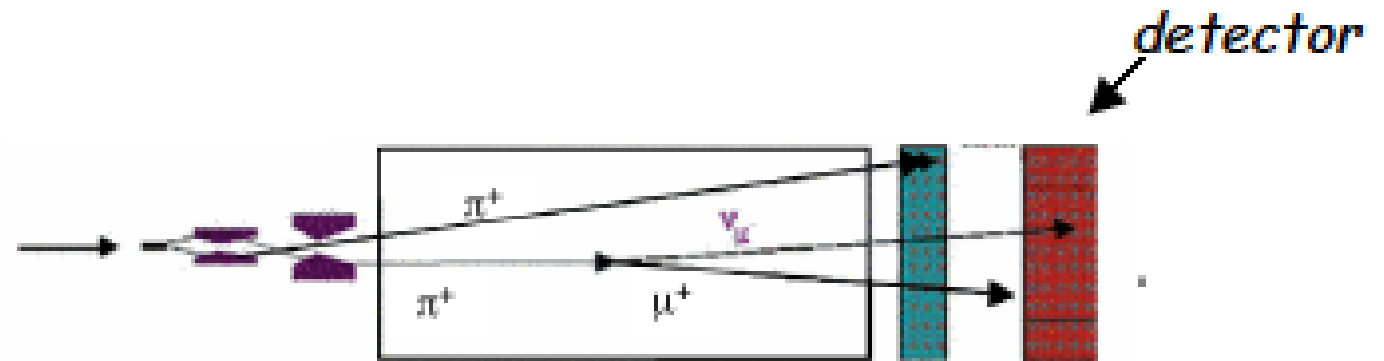
Pure muon neutrino (antinu) source, pulsed, directed

Reactor Spectra
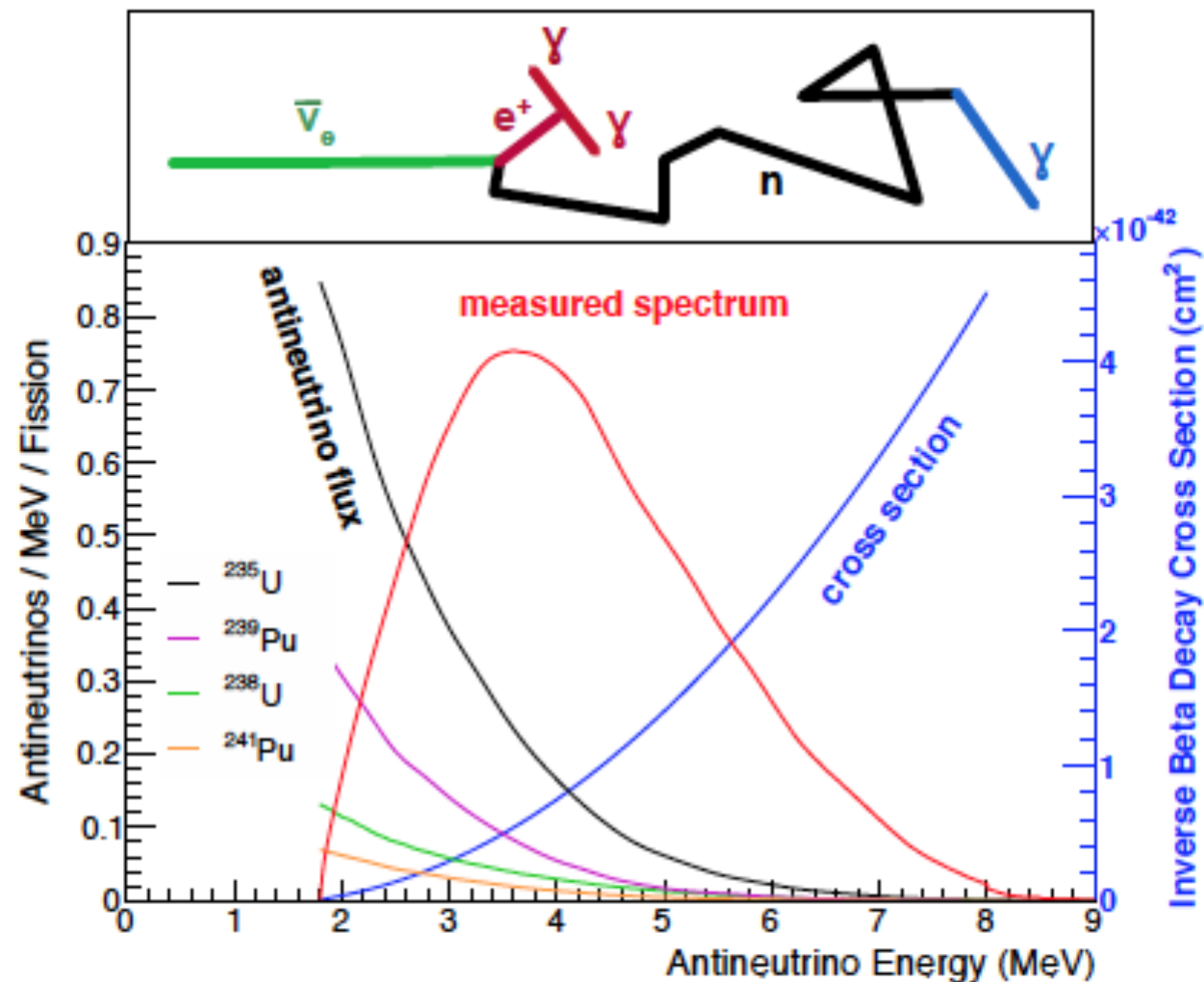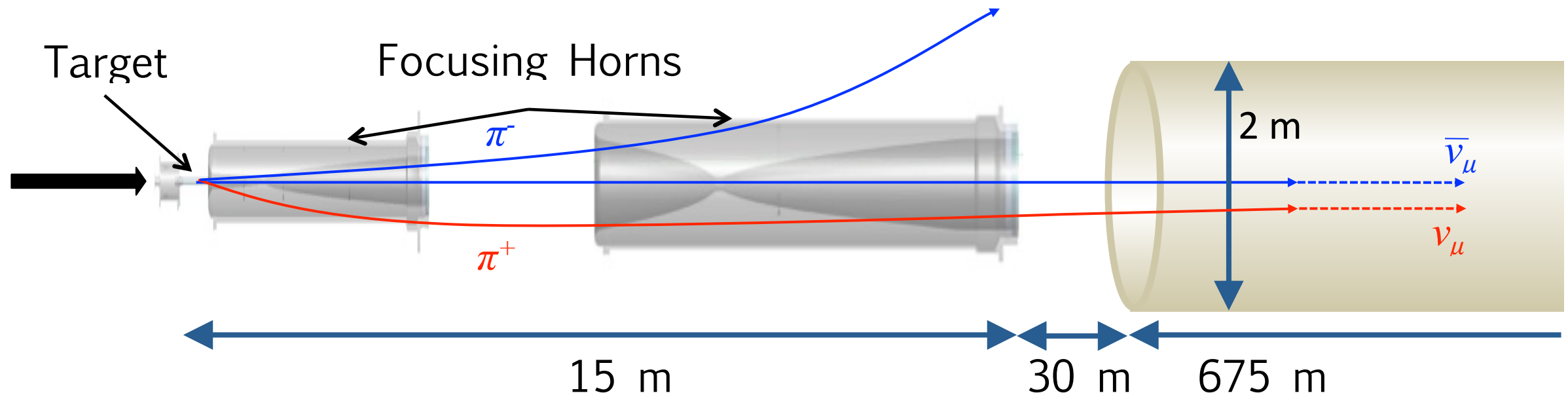

Power reactors produce 3 GW of thermal energy.

Each fission has ~200 MeV.

Each fission leads to 6 beta decays.

$$Neutrinos/\sec = 6\frac{3\times10^{9}\,J/\sec}{1.6\times10^{-13}\,J/MeV \bullet 200\,MeV}$$

Find how to calculate the spectrum from literature. (P. Vogel et al.)
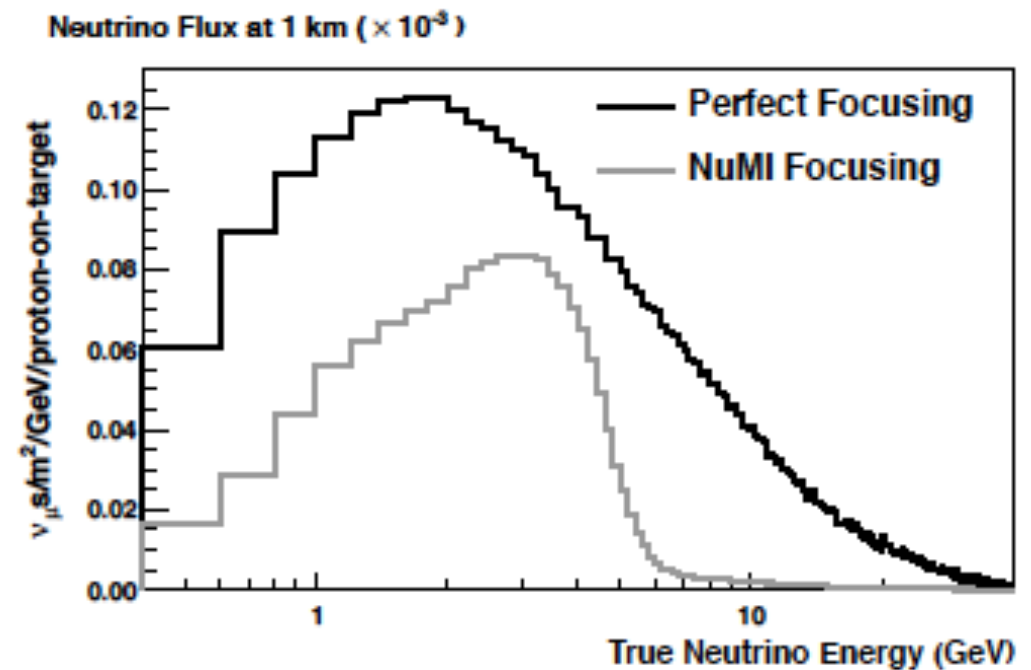
Accelerator Neutrino beam

Target

Focusing Horns

π^-

π^+

2 m

$\overline{\nu}_\mu$

ν_μ

15 m   30 m   675 m

Pions are produced in proton-carbon collisions.

Imagine each pion that emerges from target can be collimated to be forward to get

$$\sim 10^{-4} m^{-2} GeV^{-1} proton^{-1} \quad @1km$$

$$POT = \frac{Power(MW) \bullet Time(10^7 \sec)}{E_{proton}(GeV) \bullet 1.6 \times 10^{-3}}$$

Neutrino Flux at 1 km (×10⁻³)

— Perfect Focusing
— NuMI Focusing

$\nu_\mu s/m^2/GeV/proton-on-target$

True Neutrino Energy (GeV)

If neutrinos have mass; the massive states need not be the same as the Weak interaction states. A neutrino could be in a classic superposition of states.

This will lead to interference effects

Flavored neutrinos

Massive Neutrinos

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_a(t) = \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t)$$

$$P(\nu_a \rightarrow \nu_b) = |<\nu_b|\nu_a(t)>|^2$$

$$= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2$$

Sufficient to understand most of the physics:

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \rightarrow \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, ... (\pi/2)$: $\Delta m^2 = 0.0025eV^2$, $E = 1GeV$, $L = 494km$.

Definition

$Appearance : \nu_a \to \nu_b \quad \Rightarrow$ Make beam type (a) and Detect (b) after some distance to see if neutrino (a) tranformed to (b).

$Dis - appearance : \nu_a \to \nu_a \quad \Rightarrow$ Make beam type (a) and Detect (a) to see how many are left after traveling some distance

- **In both cases we must know how many (a) type were created and sent to the far detector. A precise prediction in the far detector is needed.**
- **In the first case, we must know if any events will fake the signature of (b) (these are called backgrounds.**
- **In the second we must know how many (a) to expect.**

Picture with θ = 45 deg
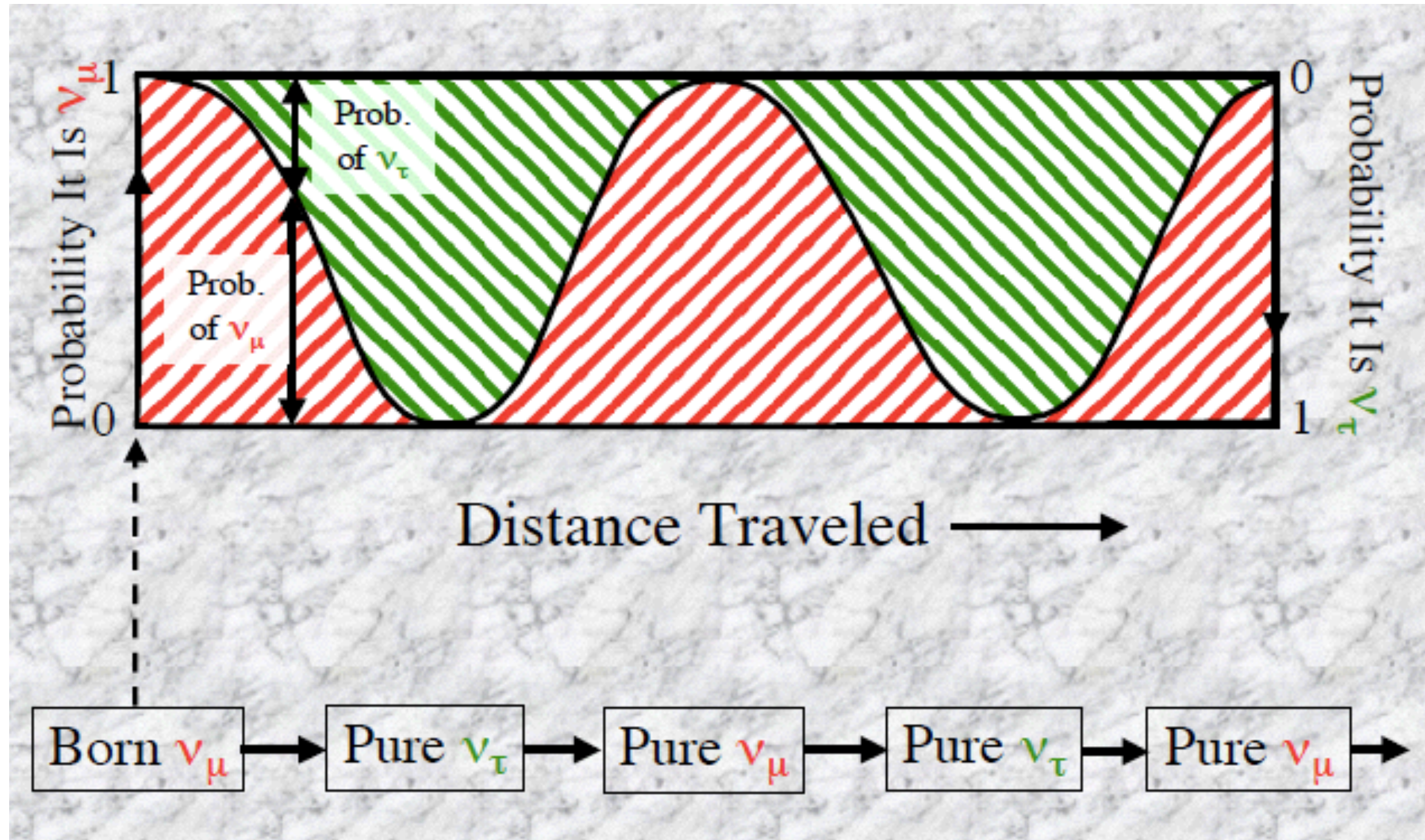
Everything we know about neutrino properties comes from this astonishing effect.
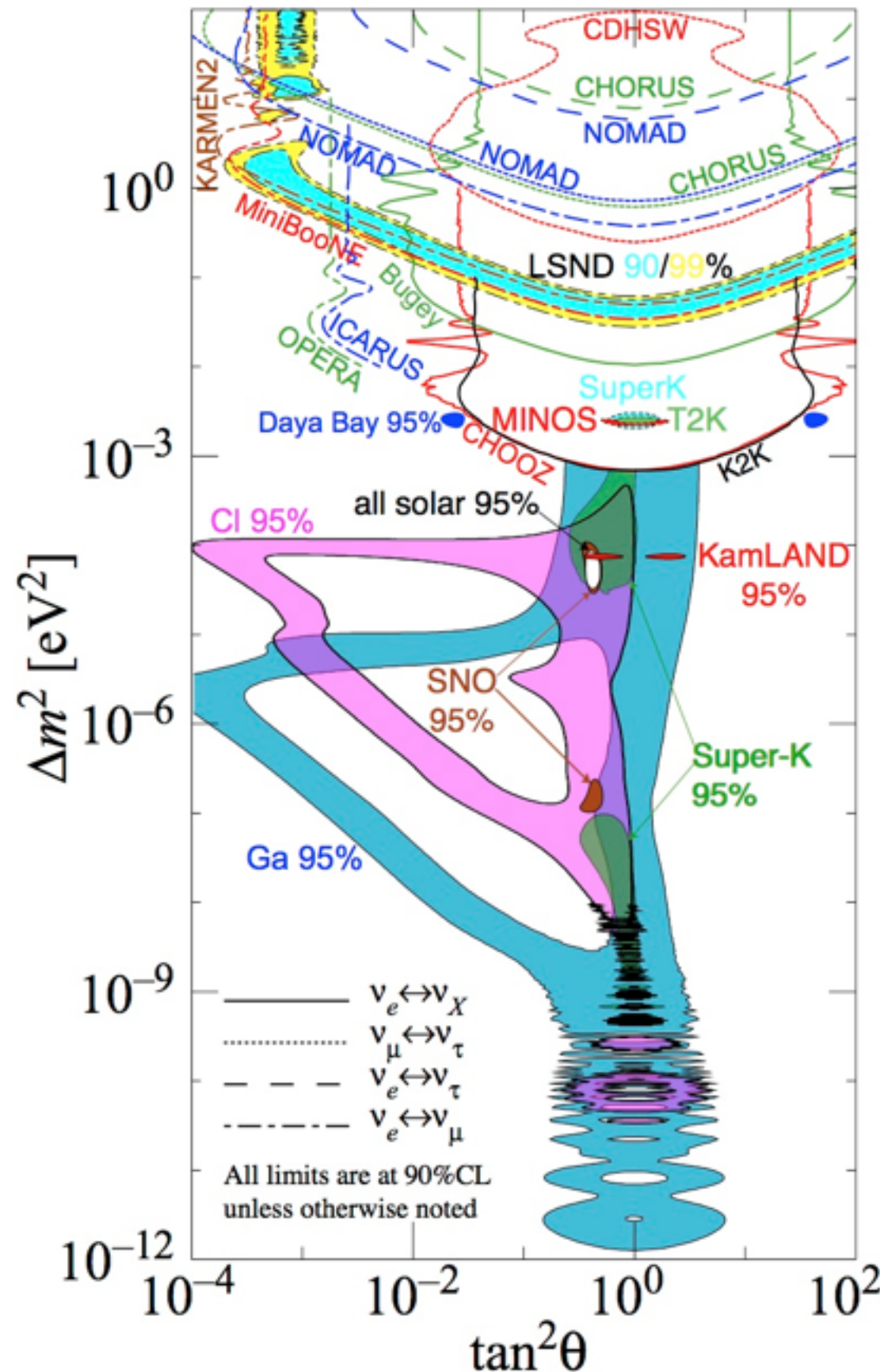
All oscillations data from PDG in two parameter plot

$$P(\nu_a \rightarrow \nu_b) = \mathrm{Sin}^2\theta\,\mathrm{Sin}^2(1.27\Delta m^2\frac{L}{E})$$
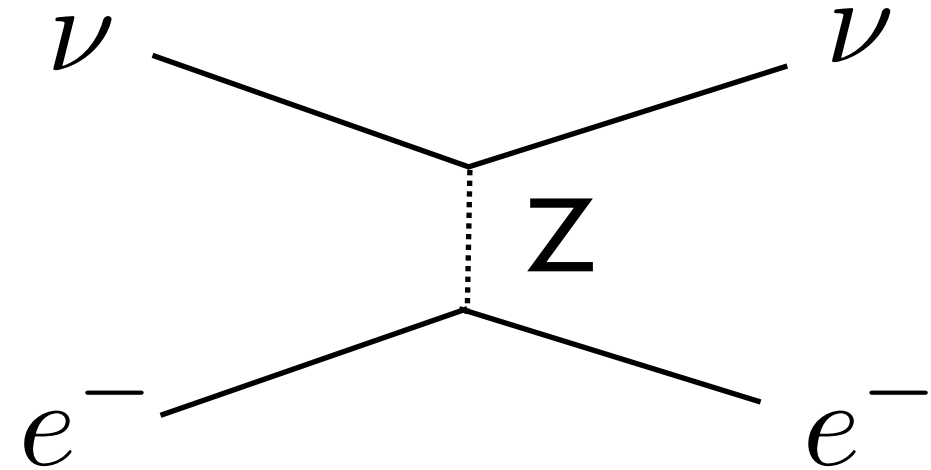
Δm^2 in eV^2

L in km

E in GeV

$$i\frac{d}{dx}\nu_f = HR_\theta\nu_m$$

L. Wolfenstein: Oscillations need to be modified in presence of matter.
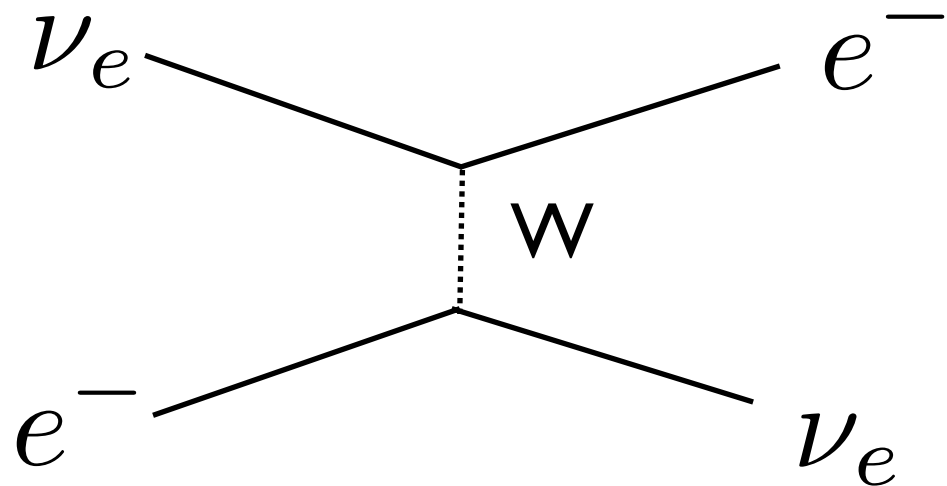
Charged Current
for electron type only

Neutral Current
for all neutrino types

Additional potential for ν_e ($\bar{\nu}_e$): $\pm\sqrt{2}G_F N_e$ =Q/2E

N_e is electron number density.

The matter effect is an example of how additional phases can affect interferometry.

Oscillations in presence of matter

$$i\frac{d}{dx}\nu_f = R_\theta H(\nu_m) + H_{mat}(\nu_f)$$

$$i\frac{d}{dx}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{1}{4E}\left(R_\theta \begin{pmatrix} m_2^2 - m_1^2 & 0 \\ 0 & m_1^2 - m_2^2 \end{pmatrix} R_\theta^T + 2E \begin{pmatrix} \sqrt{2}G_F N_e & 0 \\ 0 & -\sqrt{2}G_F N_e \end{pmatrix} \right)\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$ (3)

Looking at conversions of muon to electron neutrinos.

$$P_{\mu\to e} = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta}\times\sin^2 \frac{L\Delta m^2}{4E}\sqrt{(a - \cos 2\theta)^2 + \sin^2 2\theta}$$

This is a signed quantity

$$\begin{aligned} a &= 2\sqrt{2}EG_F N_e/\Delta m^2 \\ &\approx 7.6 \times 10^{-5} \times D/(gm/cc) \times E_\nu/GeV/(\Delta m^2/eV^2) \end{aligned}$$ (4)

This effect present if electron neutrinos in the mix

2 neutrinos with matter effect.

P (mu → e)

With matter 3 gm/cc and a> 0

No matter

Energy / GeV
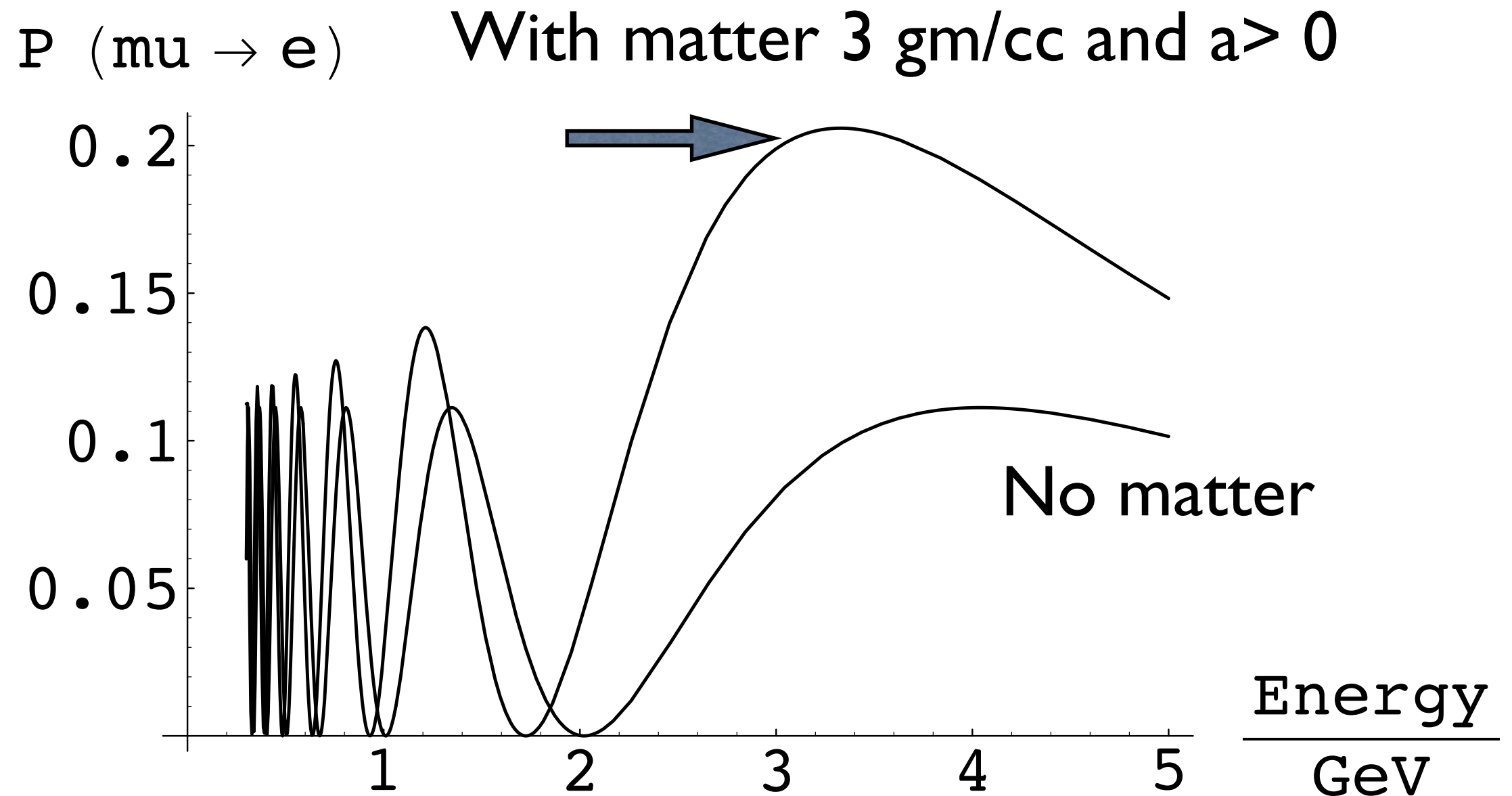
Osc. probability: 0.0025 eV^2, L= 2000 km, Theta=10deg

So Far….

- 3 types of neutrinos

- Still many unknowns about these particles, but they play an important role in the early universe as well as current astrophysical processes.

- If they have mass there are fundamental consequences.

- Oscillation phenomenology

- In next slides I will review the complete picture of the 3 neutrinos: masses and mixing.

Located in a deep mine ~ 6000 mwe because solar nu < 14 MeV

1 kT D2O Heavy Water

Sudbury Neutrino Observatory
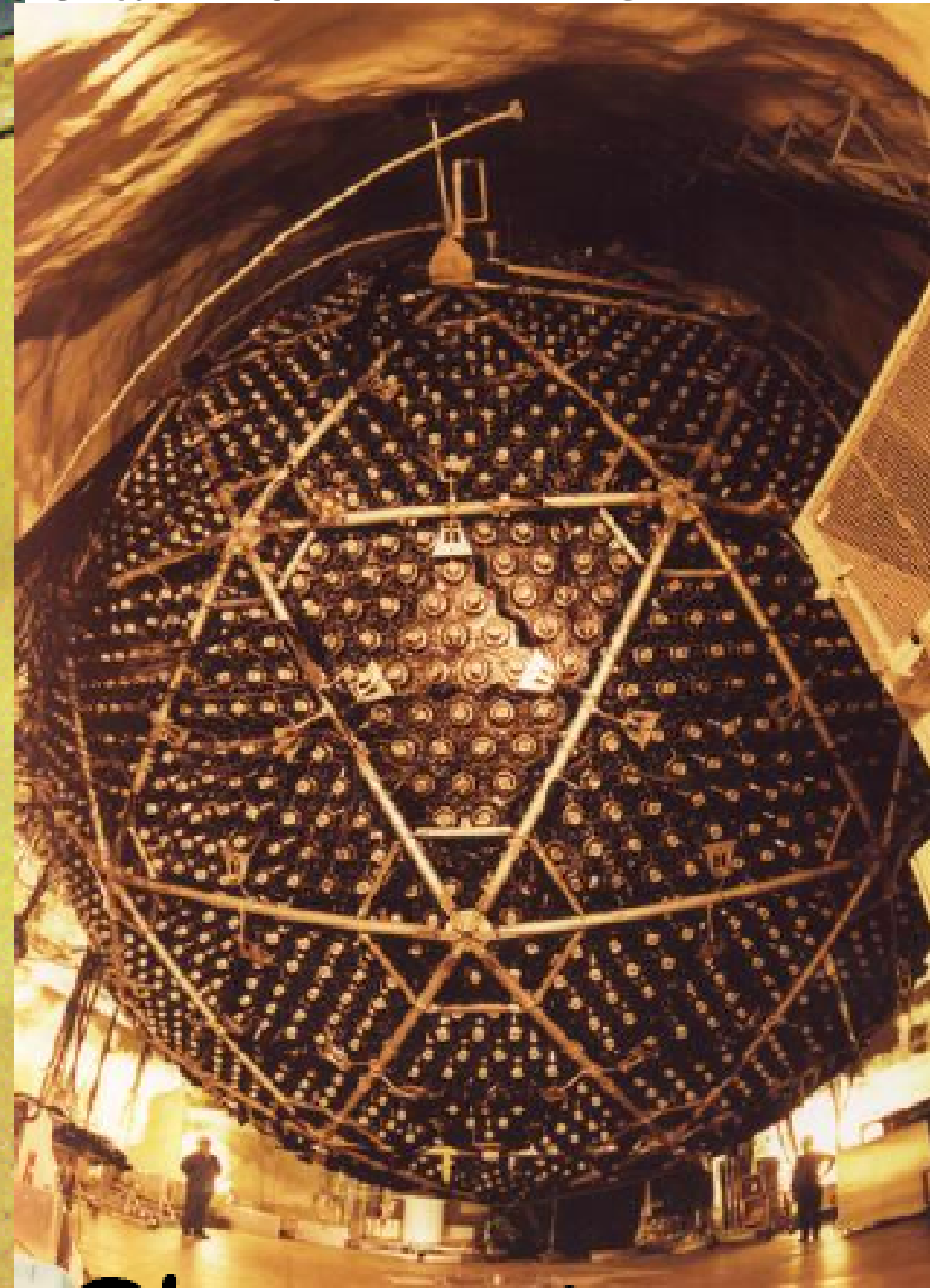
Why does SNO use $300M worth of heavy water?

The Sun is known to emit electron neutrinos.

About 10^{11} /cm^2/sec,
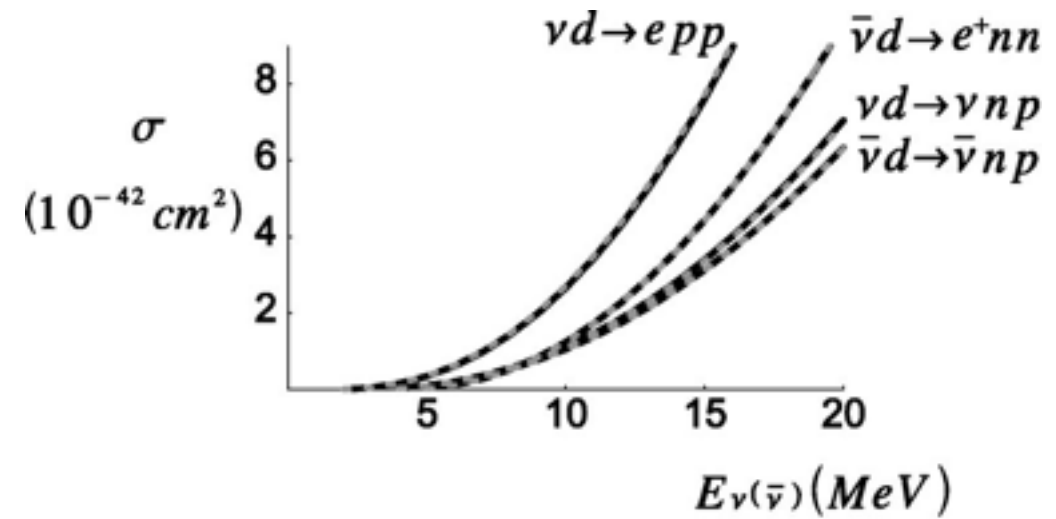
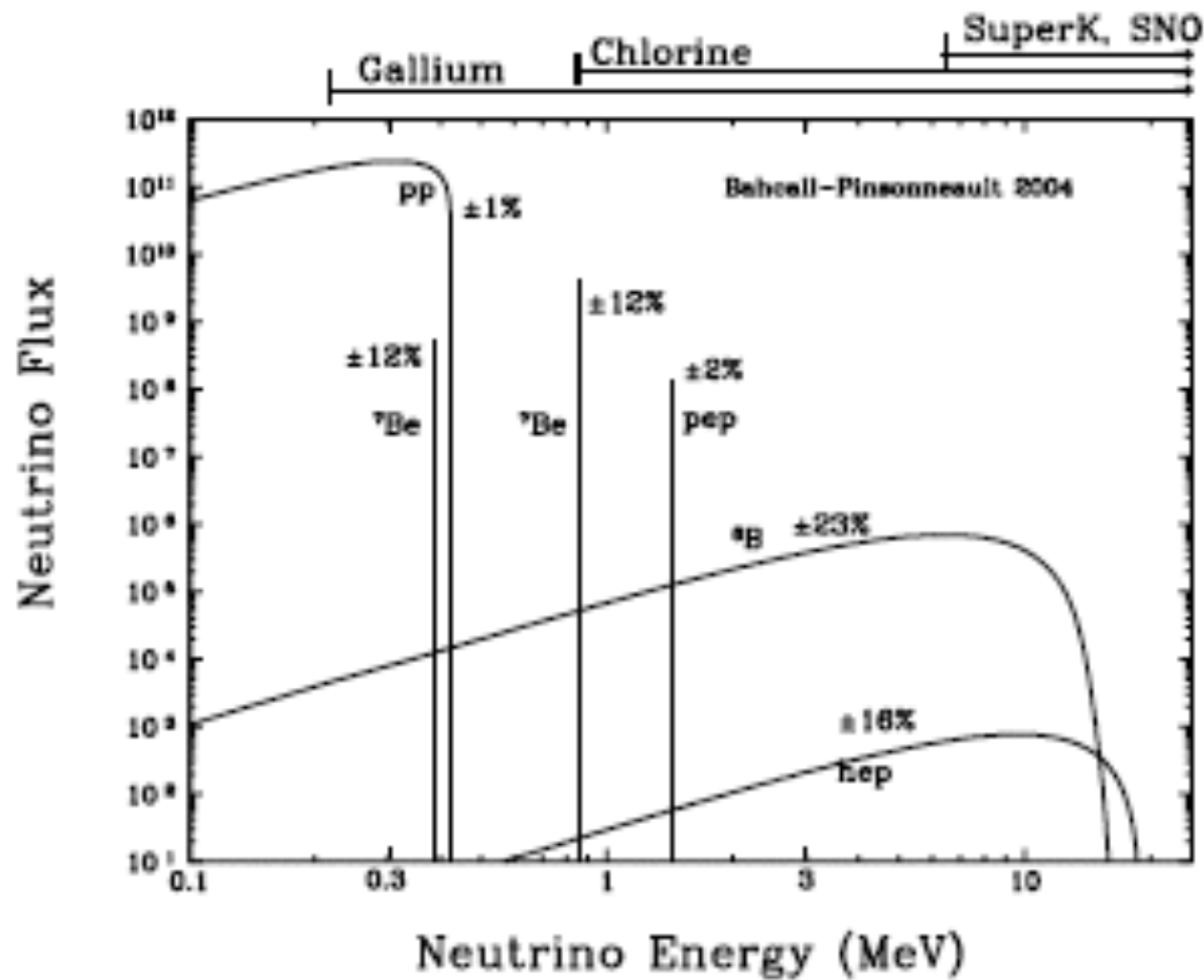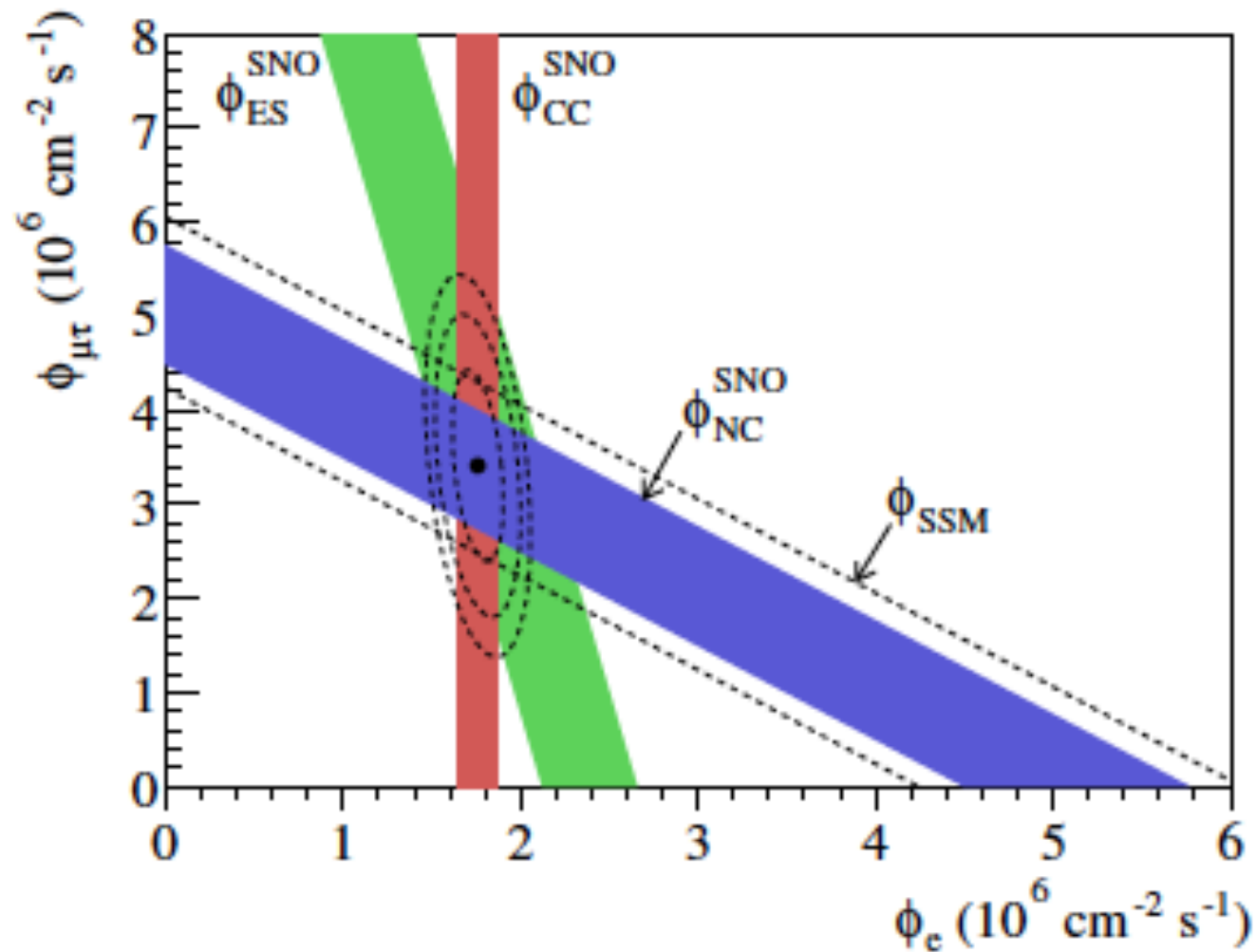But only a fraction are above practical detection threshold.

ν_e e

W p

d p

Charged Current

ν_e, ν_μ, ν_τ ν_e, ν_μ, ν_τ
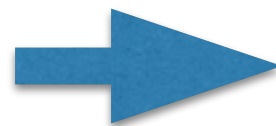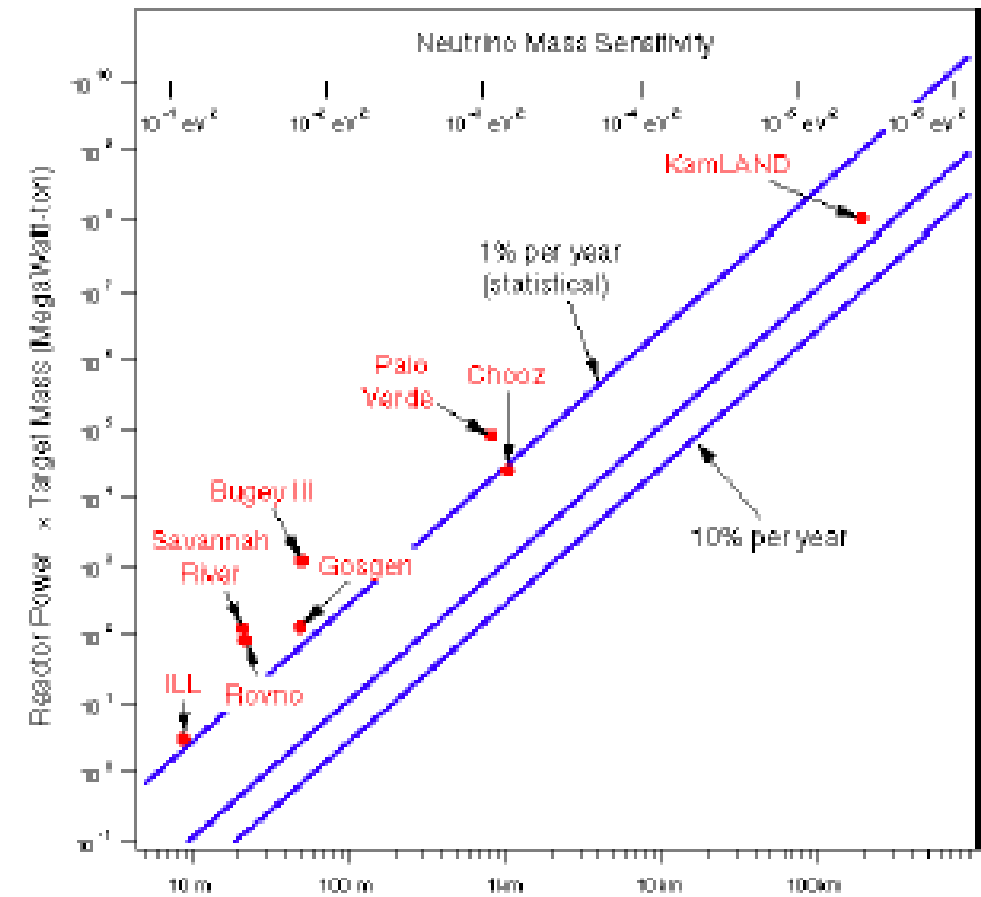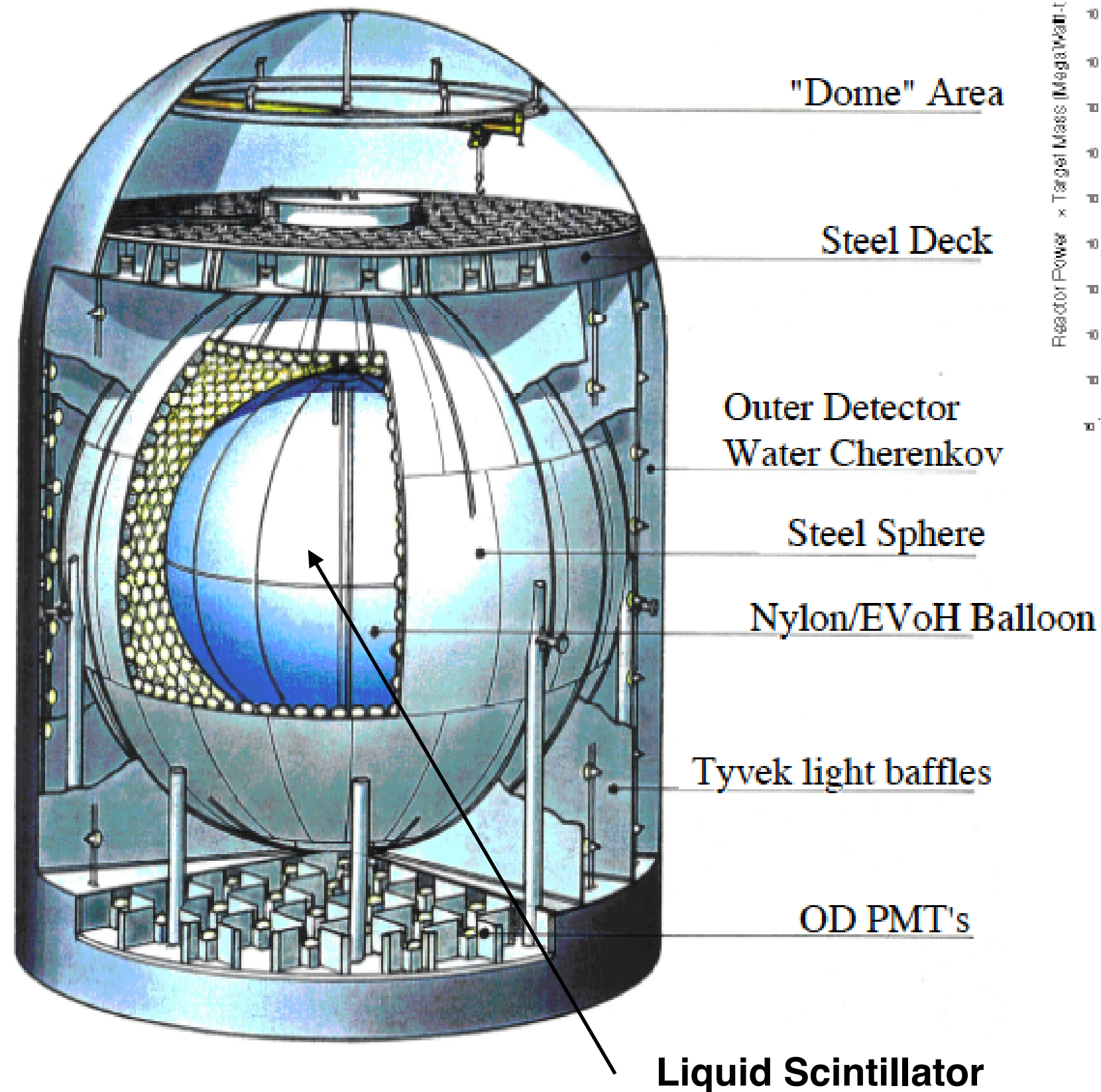
Z n

d p
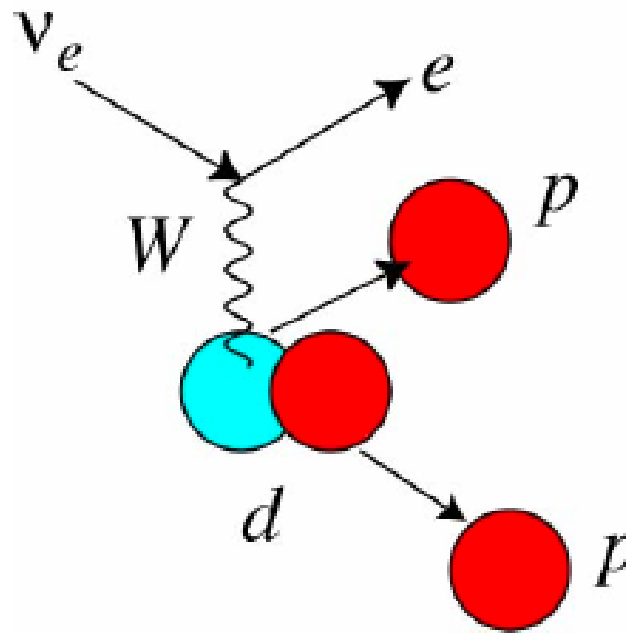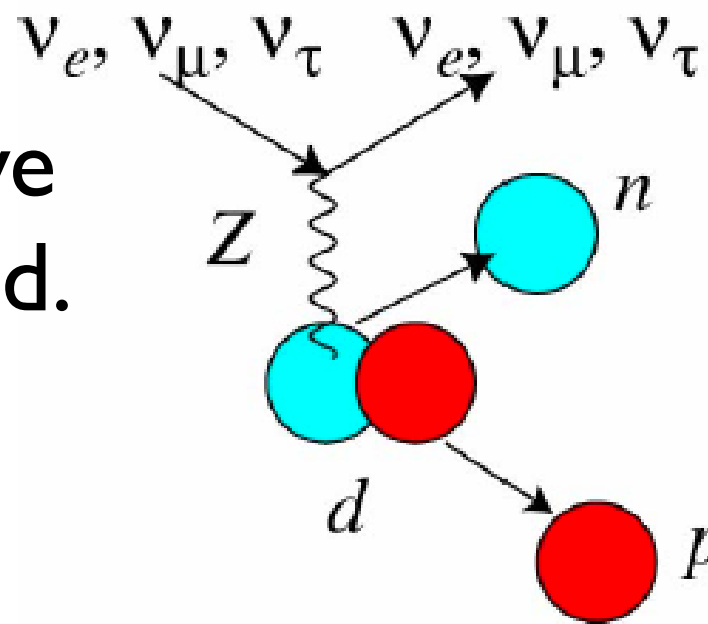
Neutral Current

Sno event rate
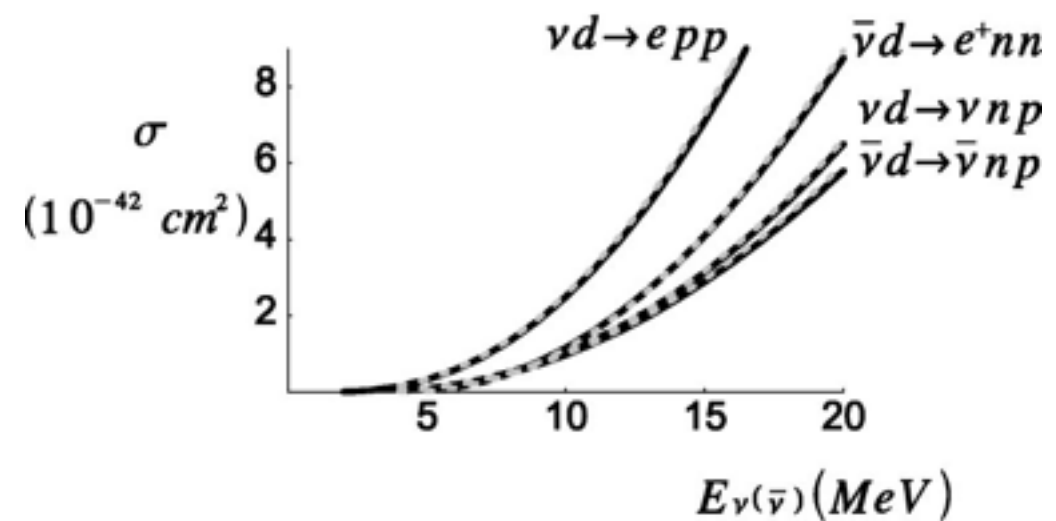
SNO data

$$\phi_{SSM} = 5.82 \pm 1.34 \times 10^6 \, cm^{-2} \sec^{-1}$$

For Boron8 Neutrinos.

~2/3 of the electron neutrinos turned into other types.

KamLAND

"Dome" Area

Steel Deck

Outer Detector
Water Cherenkov

Steel Sphere

Nylon/EVoH Balloon

Tyvek light baffles

OD PMT's

Liquid Scintillator

Neutrino Mass Sensitivity

10^{-1} eV^2 10^{-2} eV^2 10^{-3} eV^2 10^{-4} eV^2 10^{-5} eV^2 10^{-6} eV^2

KamLAND

1% per year
(statistical)

Palo
Verde   Chooz

Bugey III

Savannah
River   Gosgen

10% per year

ILL   Rovno

Reactor Power × Target Mass (MegaWatt-ton)

10 m   100 m   1 km   10 km   100 km

Baseline

Reactors are prolific sources of anti-neutrinos ~10^{20}/GW$_{th}$/sec

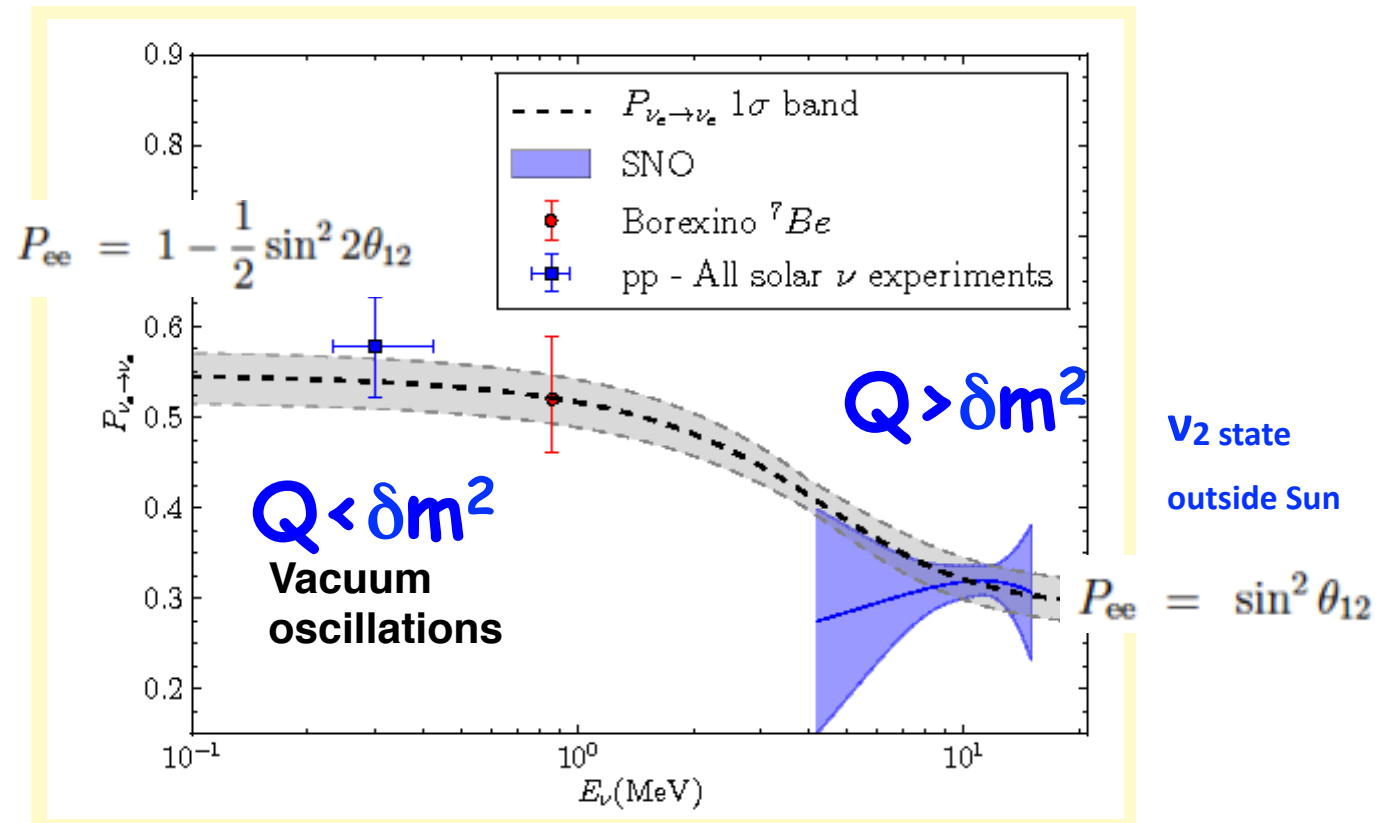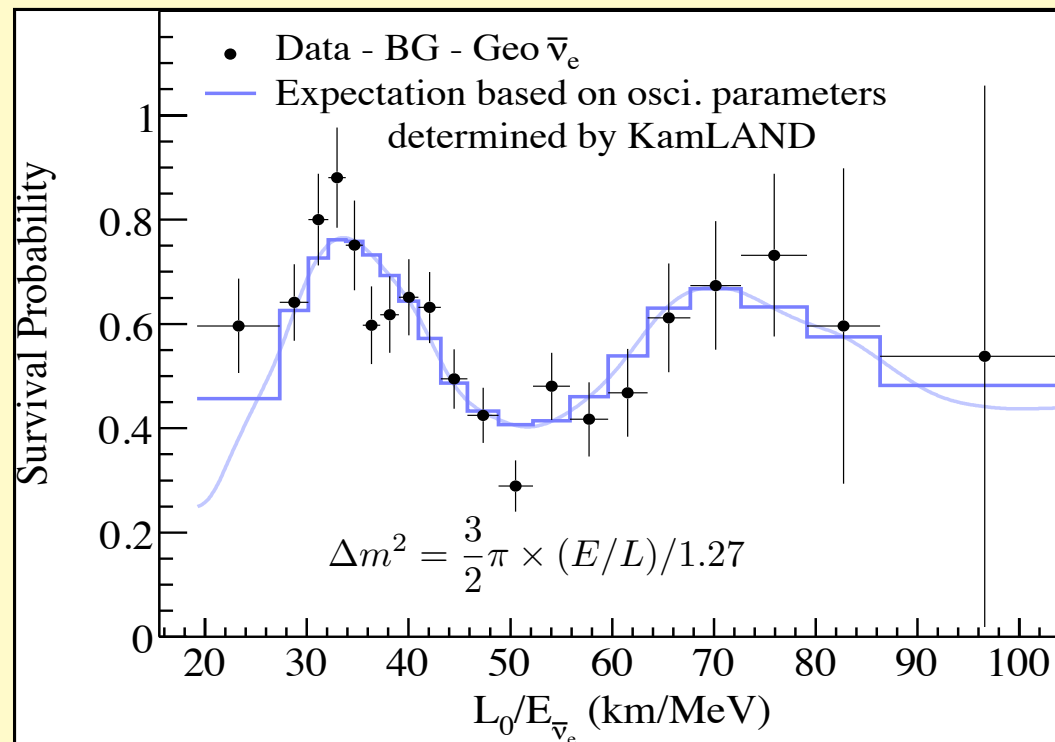$$\overline{\nu}_e + p \rightarrow e^+ + n$$
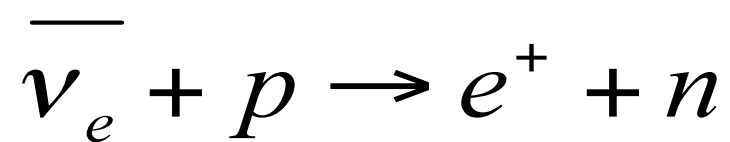
The detection reaction is inverse beta decay. The final state neutron is also detected thru absorption on hydrogen.
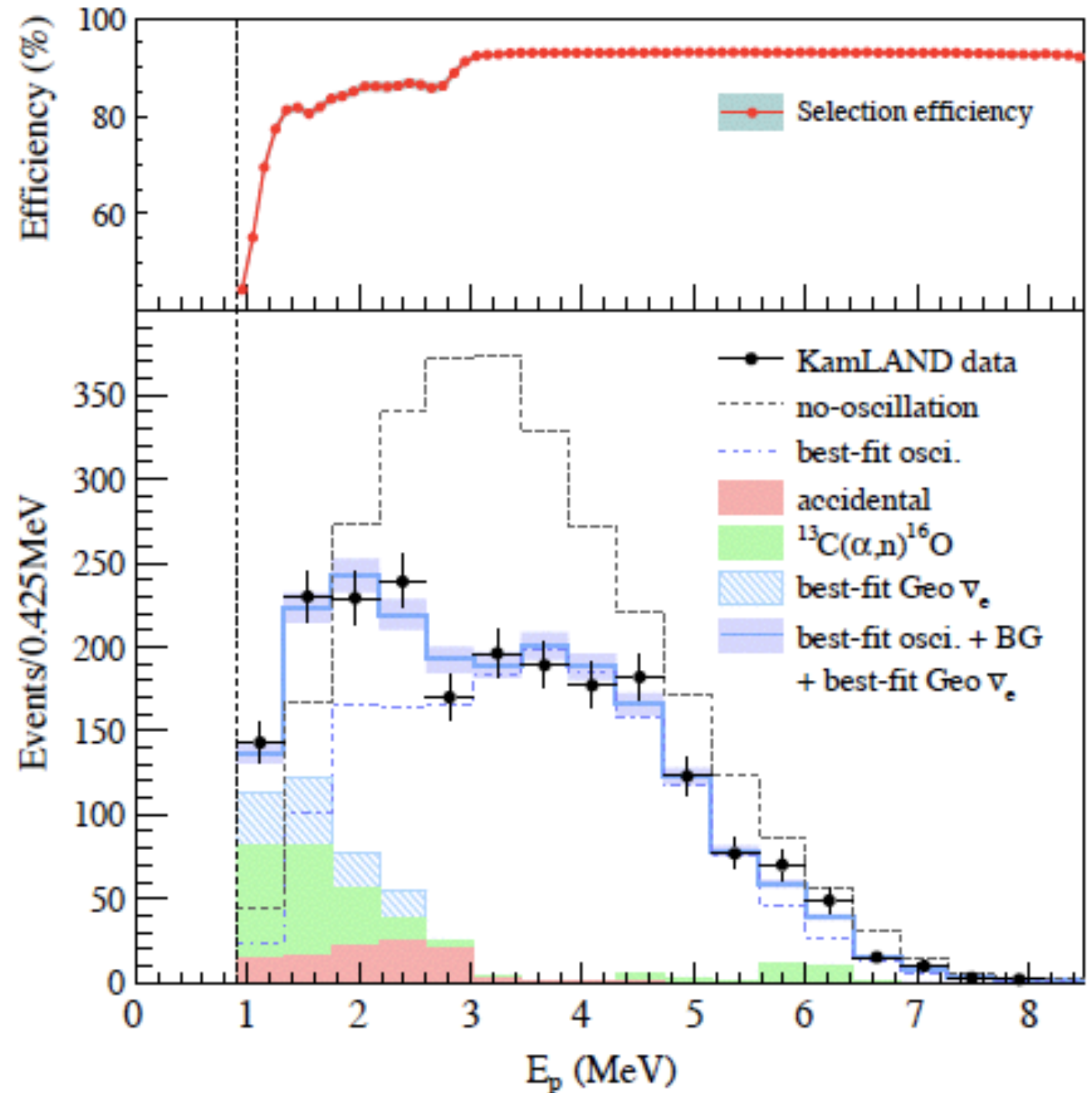
1009:4771

The ν_e state

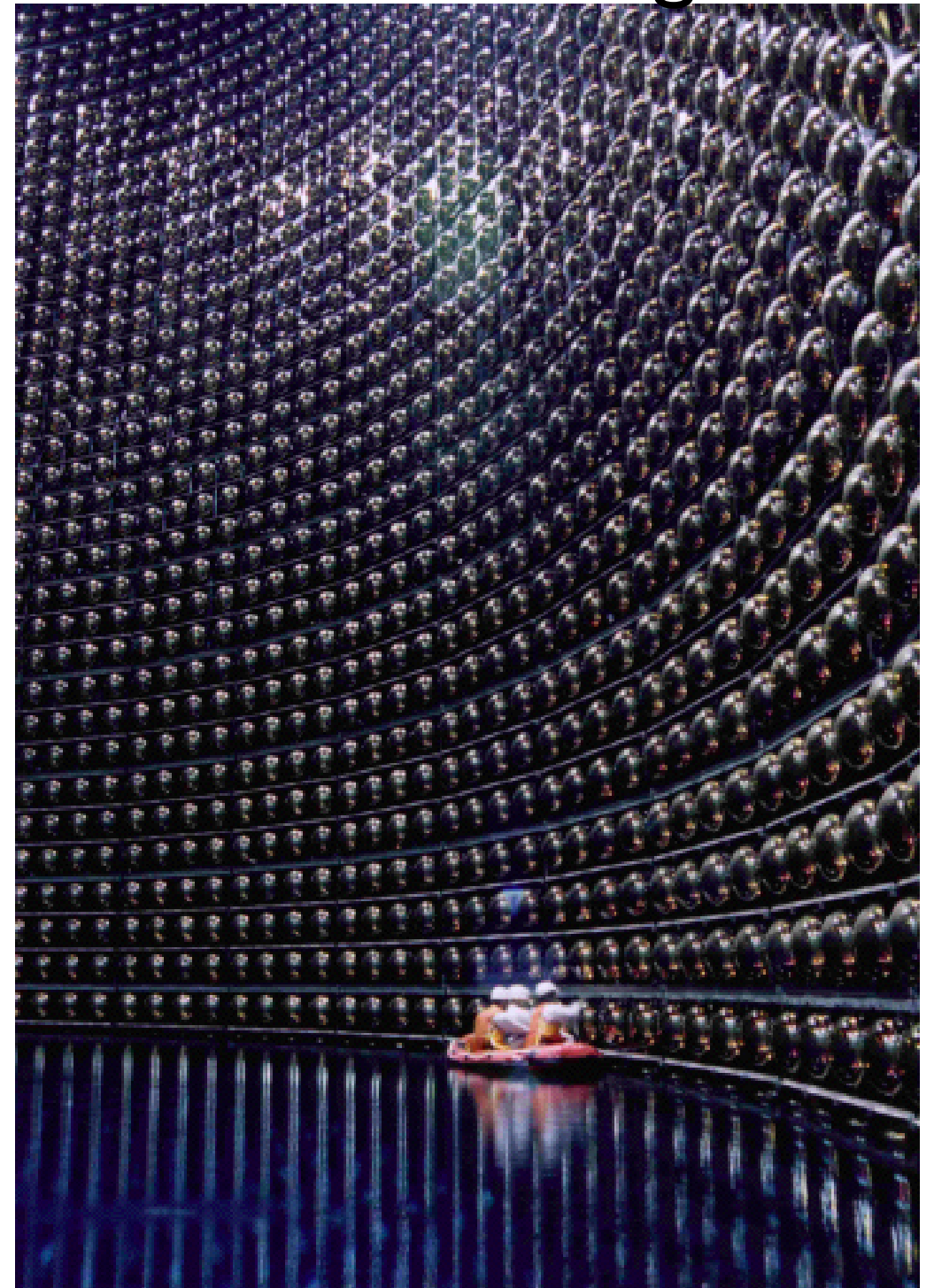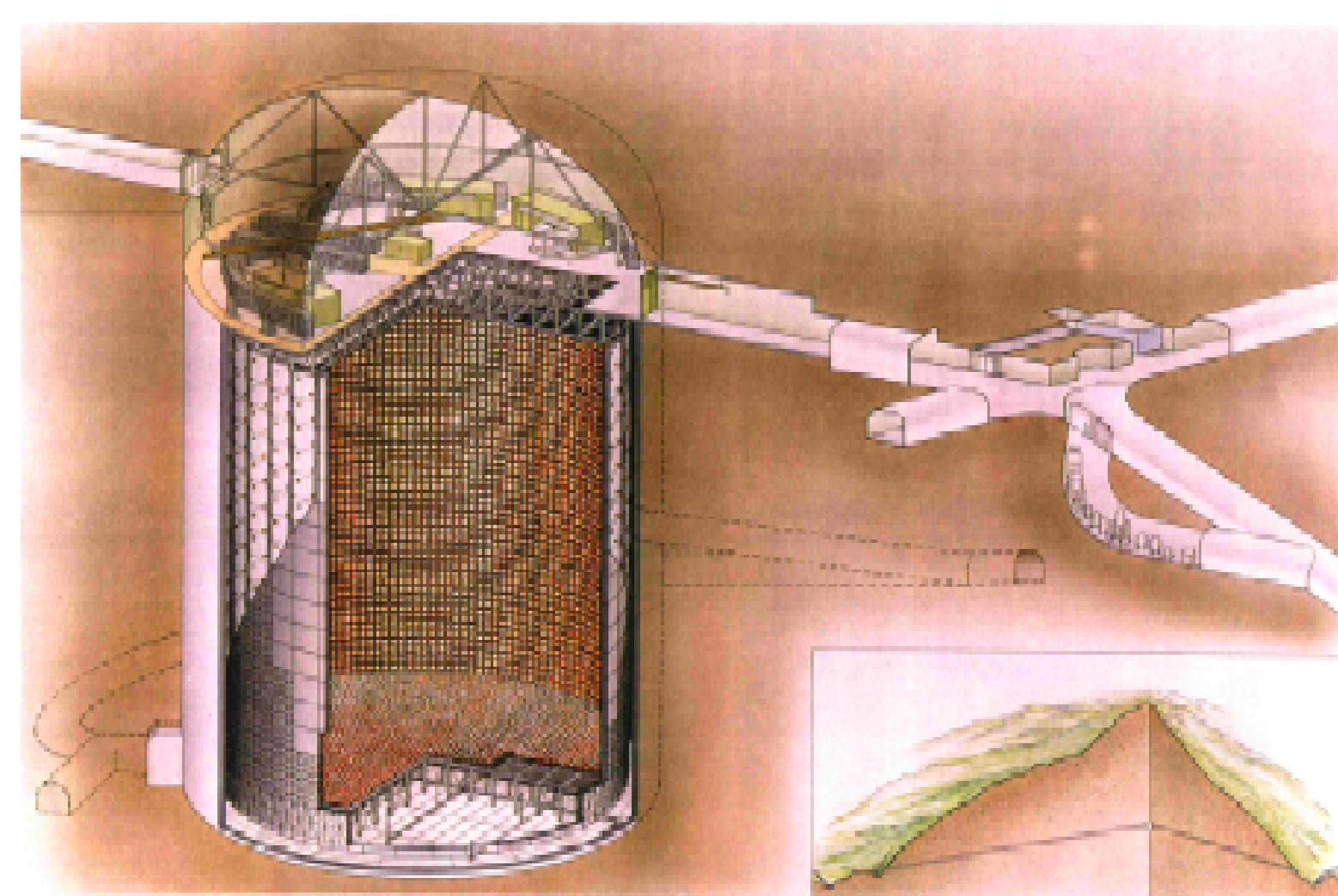- $\nu_e \sim 0.82\,\nu_1 + 0.55\,\nu_2 + e^{-i\delta}\,0.16\,\nu_3$

Kamland Reactor data determines the first two elements of this mixing with a well-defined frequency or mass splitting. Data from the Sun (SNO, Borexino, Gallium) is needed to determine which one is heavier !

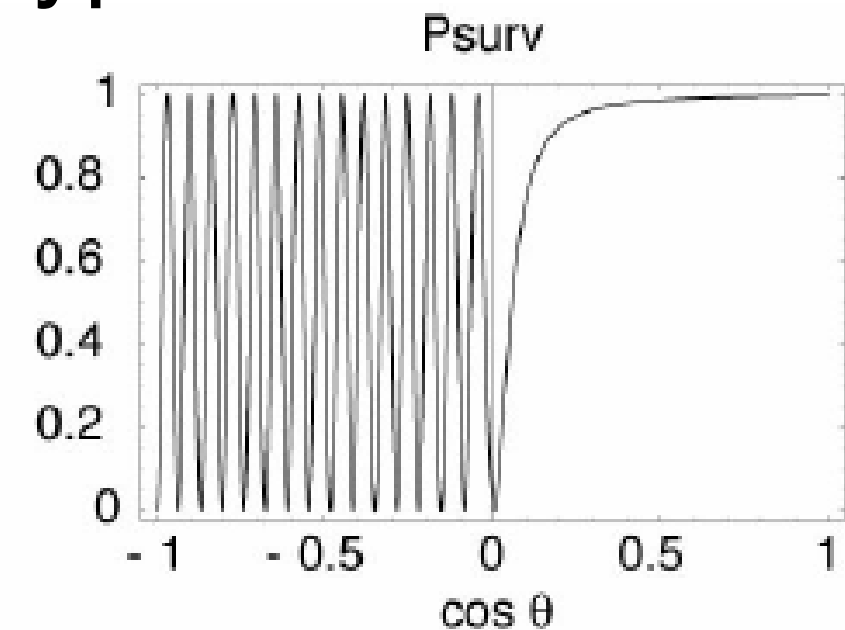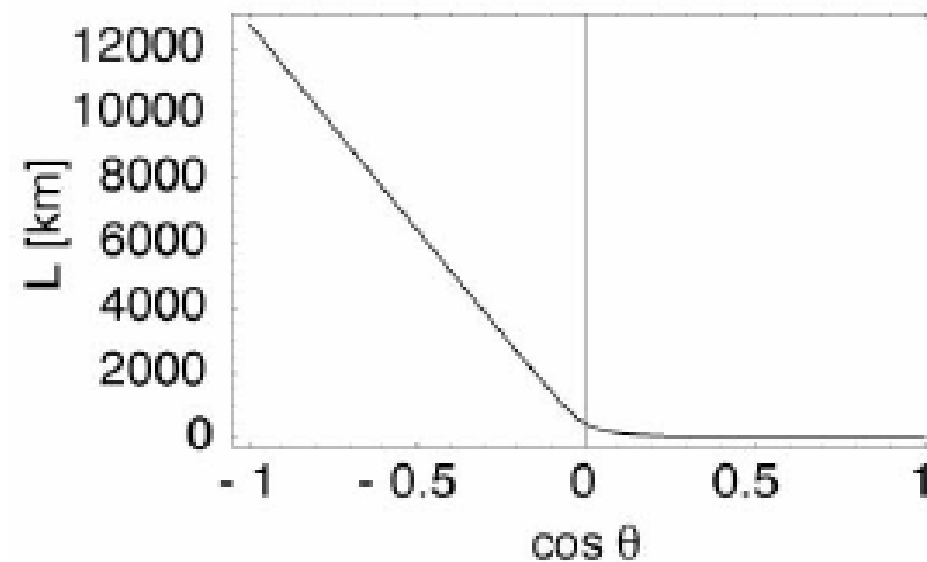$\delta m^2 = m^2_2 - m^2_1 \sim 7.5 \times 10^{-5}\,eV^2$ $\qquad \theta_{12} \approx 35^o$
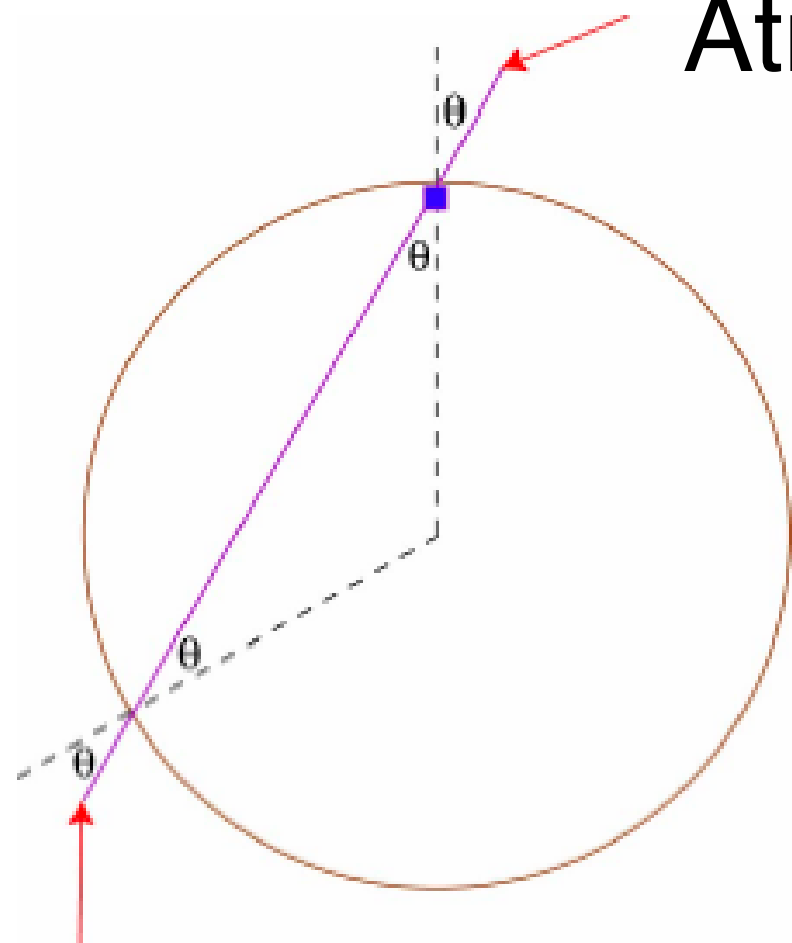
SuperKamiokaNDE
50,000 tons of water
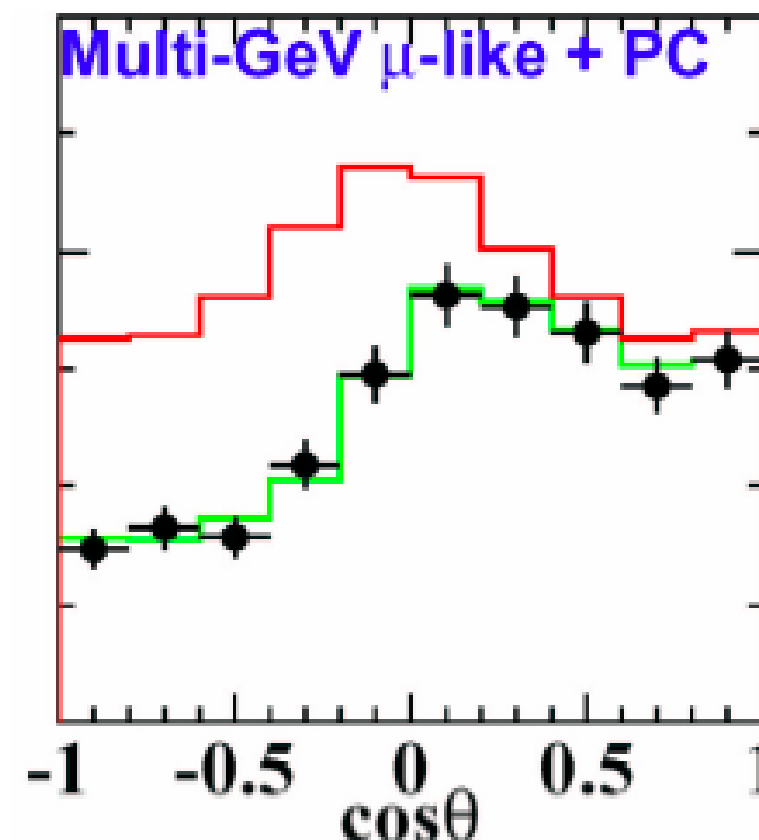11000 photomultipliers
Cherenkov light

Atmospheric neutrinos as a source for oscillation experiments

Atm. neutrinos 2:1 mu:e type

Flux inside uniformly illuminated spherical shell is constant and isotropic everywhere in the volume

There is no surplus of electrons
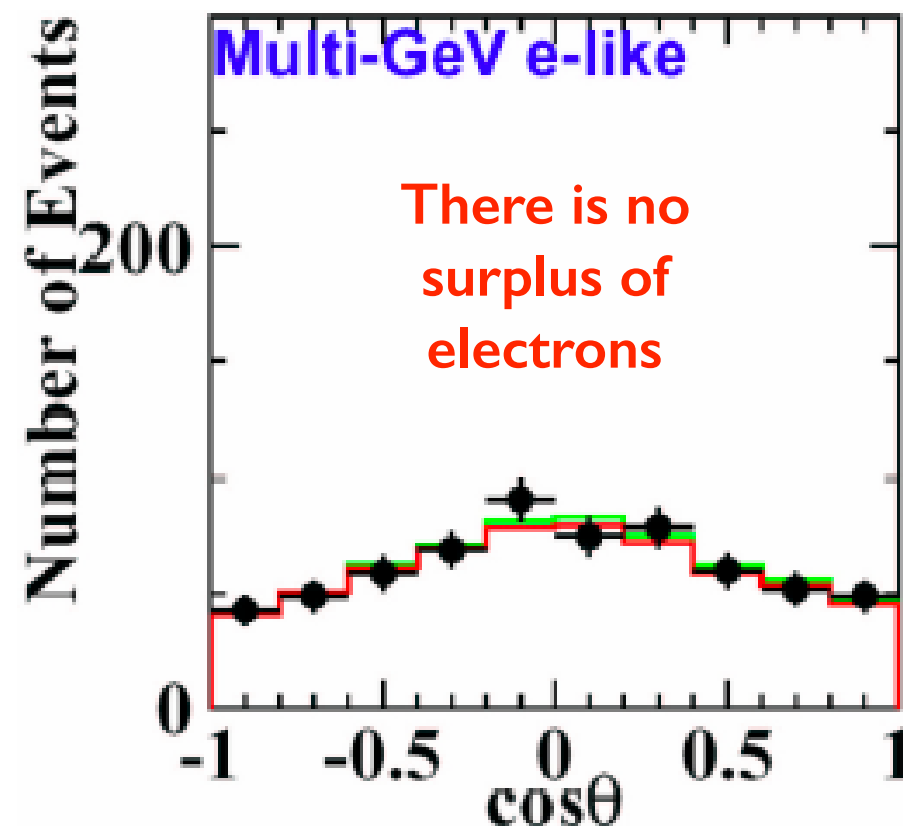
Muon neutrinos coming from below disappear

Evidence for neutrino oscillations from SuperK

MINOS

- Prepare a pure beam of muon neutrino beam.

- Aim it towards a large muon detector.

- Observe spectrum of muon neutrinos to see oscillations in energy.

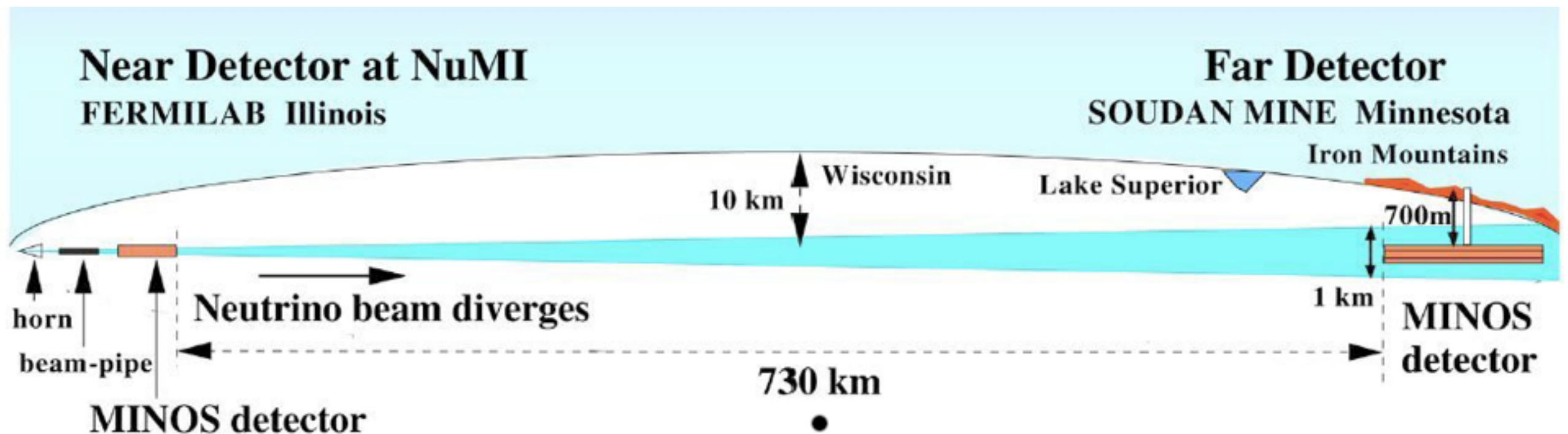# MINOS Detectors
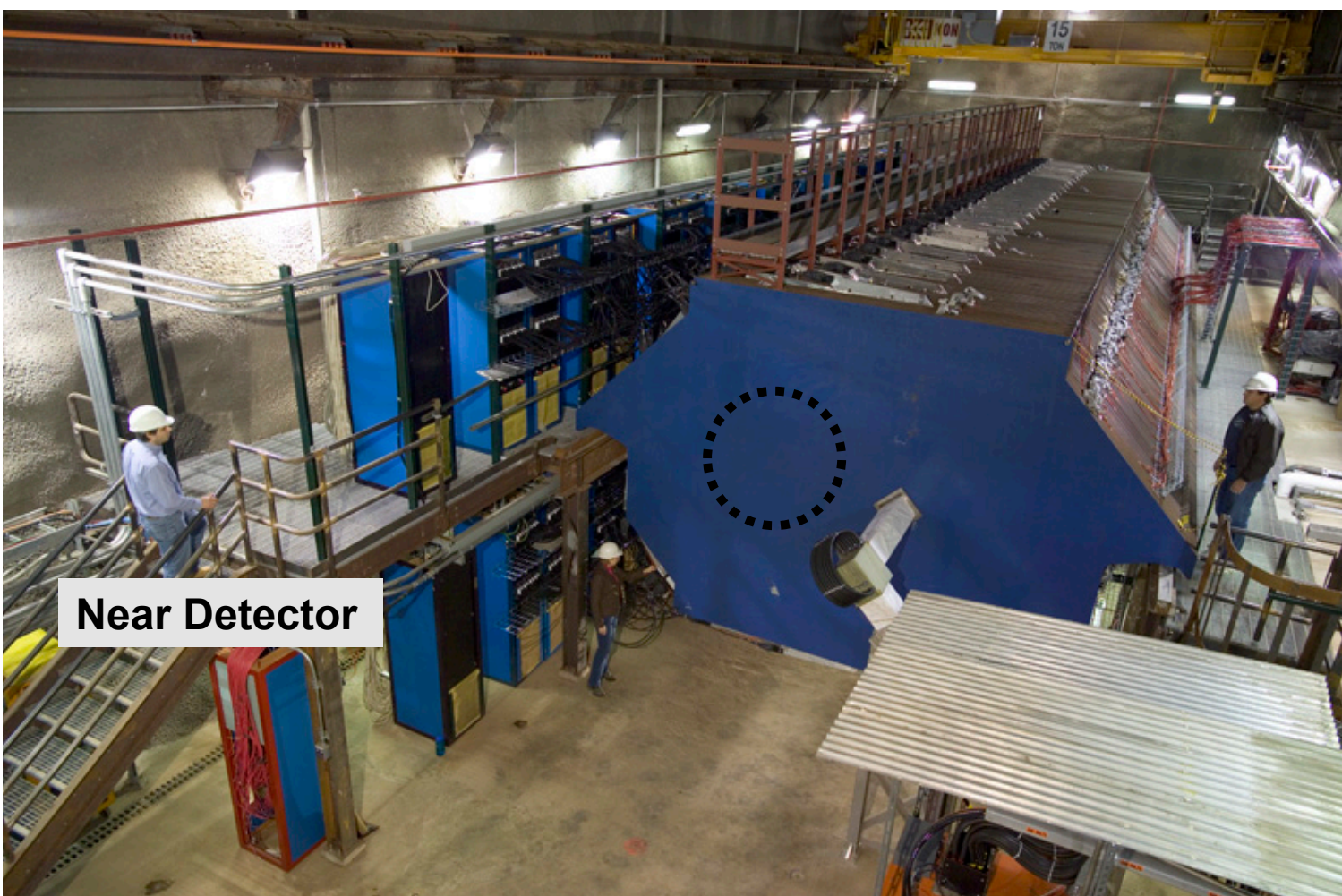
Near Detector

Far Detector

485

33
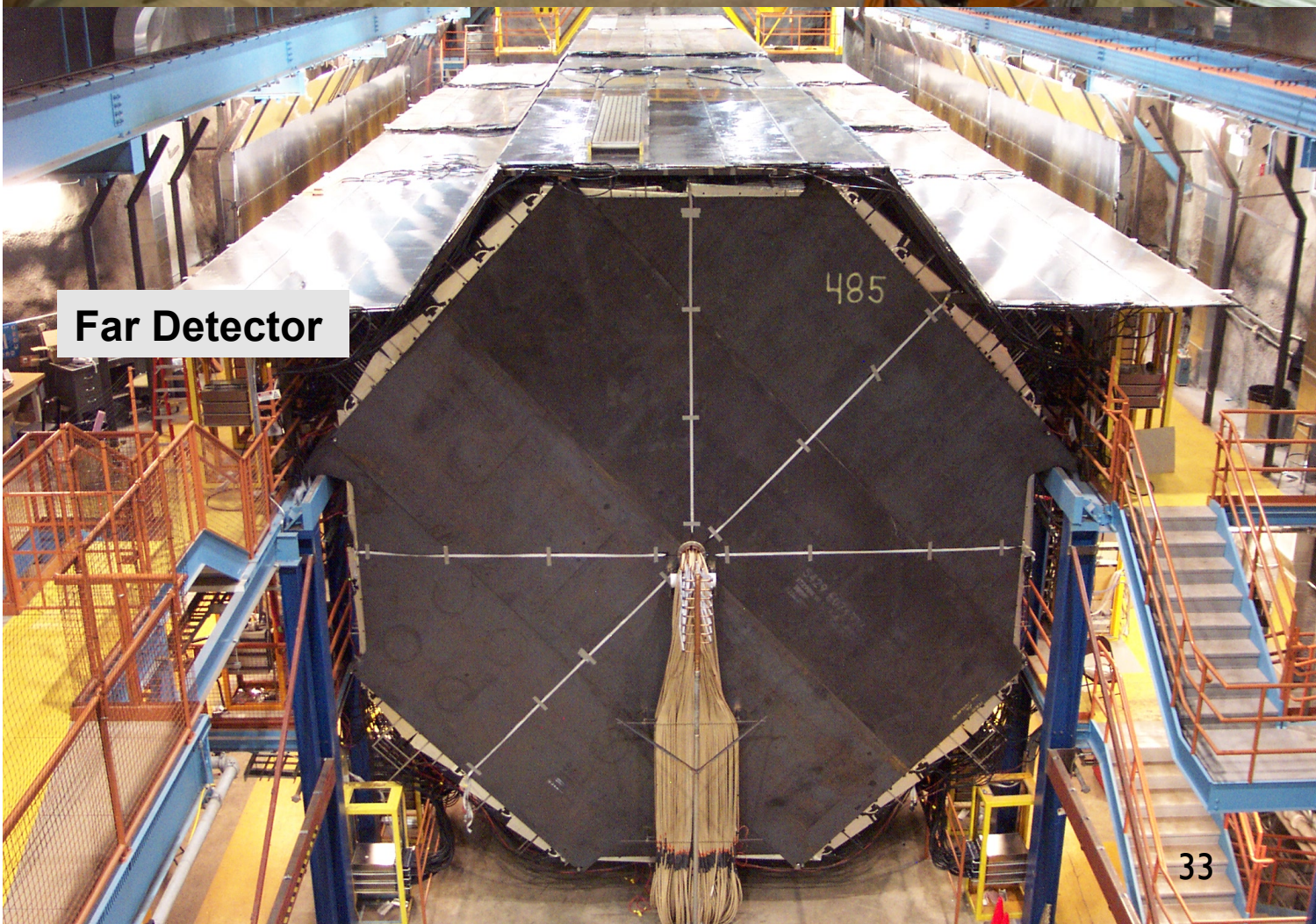
- Massive
  - 1 kt Near detector (small fiducial)
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
    - 1 Muon ~ 27 planes
    - 1.4 radiation lengths
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
    - Molier radius ~3.7 cm

- Wavelength shifting fibre optic readout
- Multi-anode PMTs
- Magnetised (~1.3 T)

The ν_μ state

- $\nu_\mu \sim -(p)0.4\ \mathbf{v}_1 + (p')0.5\ \mathbf{v}_2 - 0.7\ \mathbf{v}_3$

In addition - Important confirmation of tau neutrino mixing came from OPERA
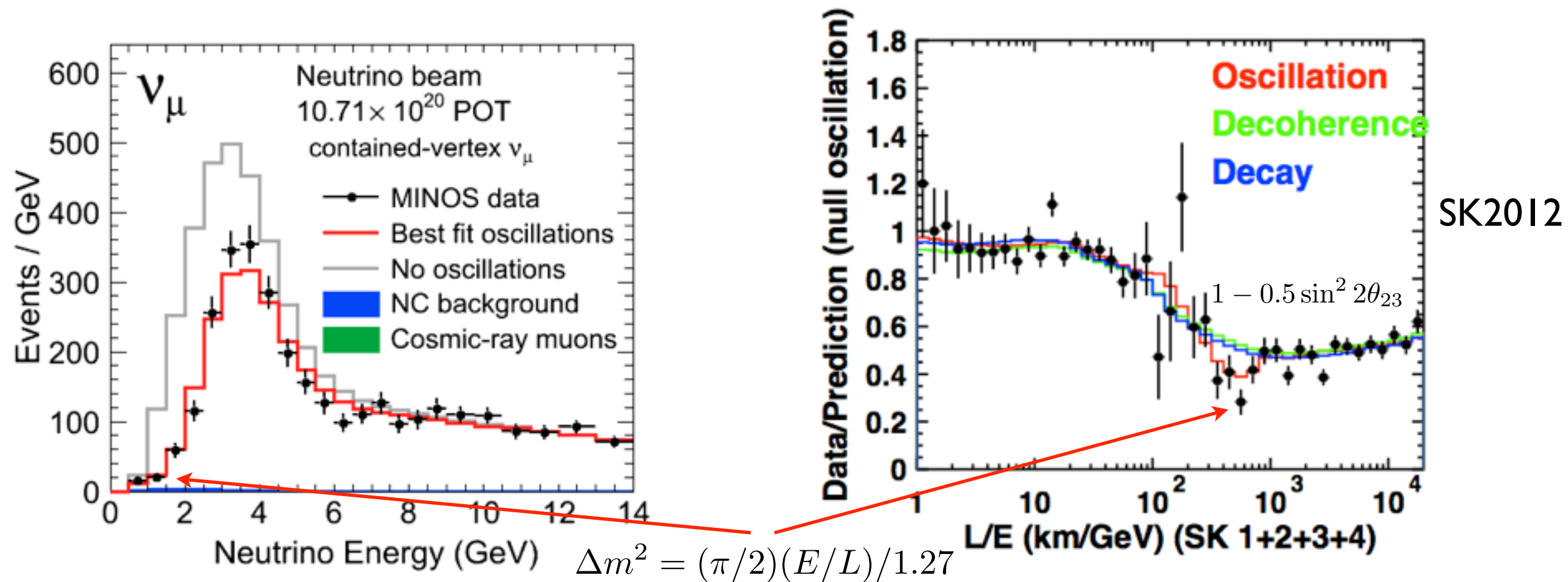

SK2012

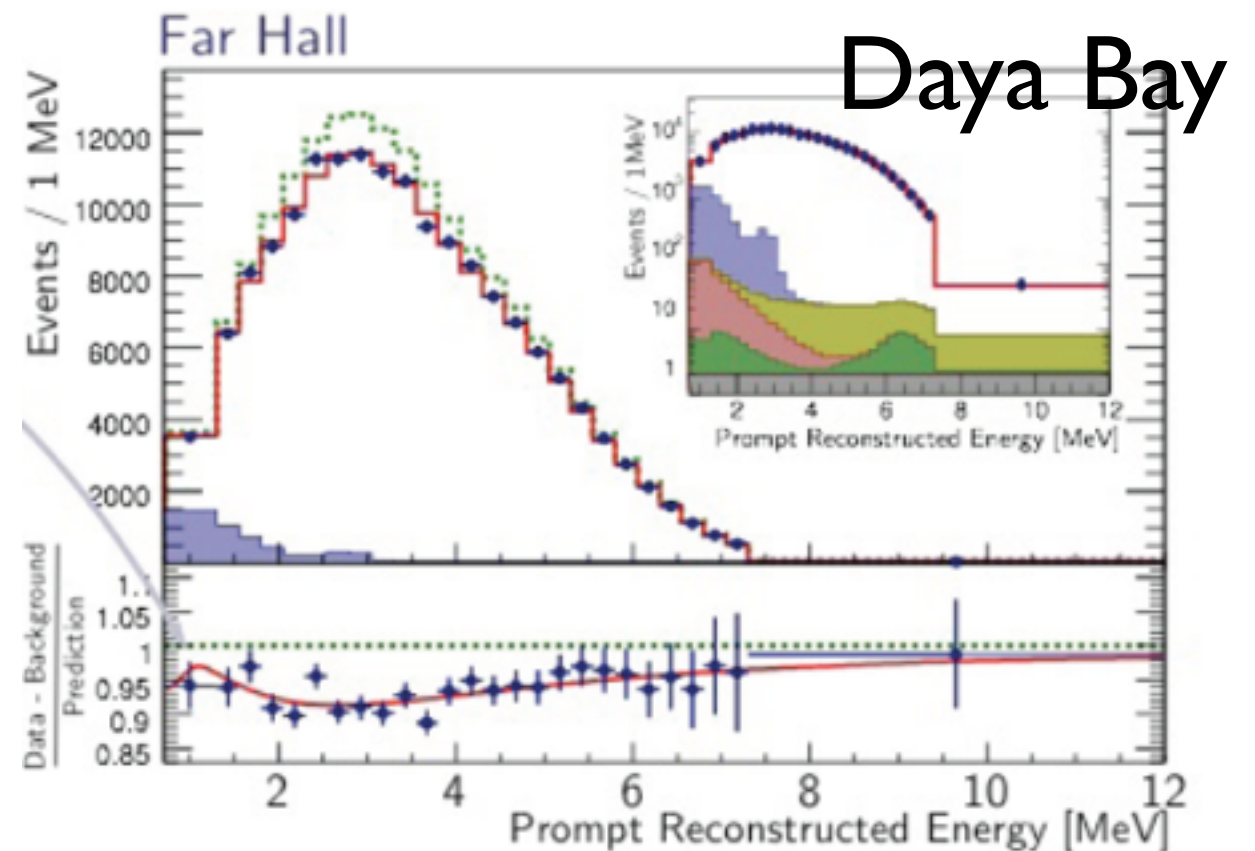$$\Delta m^2 = (\pi/2)(E/L)/1.27$$

$$1 - 0.5\sin^2 2\theta_{23}$$

Accelerator MINOS data provides precise difference of mass for the third element, and atmospheric SuperK data shows the mixing to be maximal, but we do not know which is heavier.

$$\Delta m^2 = |m_3^2 - m_{1,2}^2| \sim 2.4 \times 10^{-3}\ eV^2 \qquad \theta_{23} \approx 45^o$$

p, p' represent phases. Cannot determine sign of mass diff.

The ν_e state again !

- $\nu_e \sim 0.82\ \nu_1 + 0.55\ \nu_2 + e^{-i\delta}\ 0.16\ \nu_3$
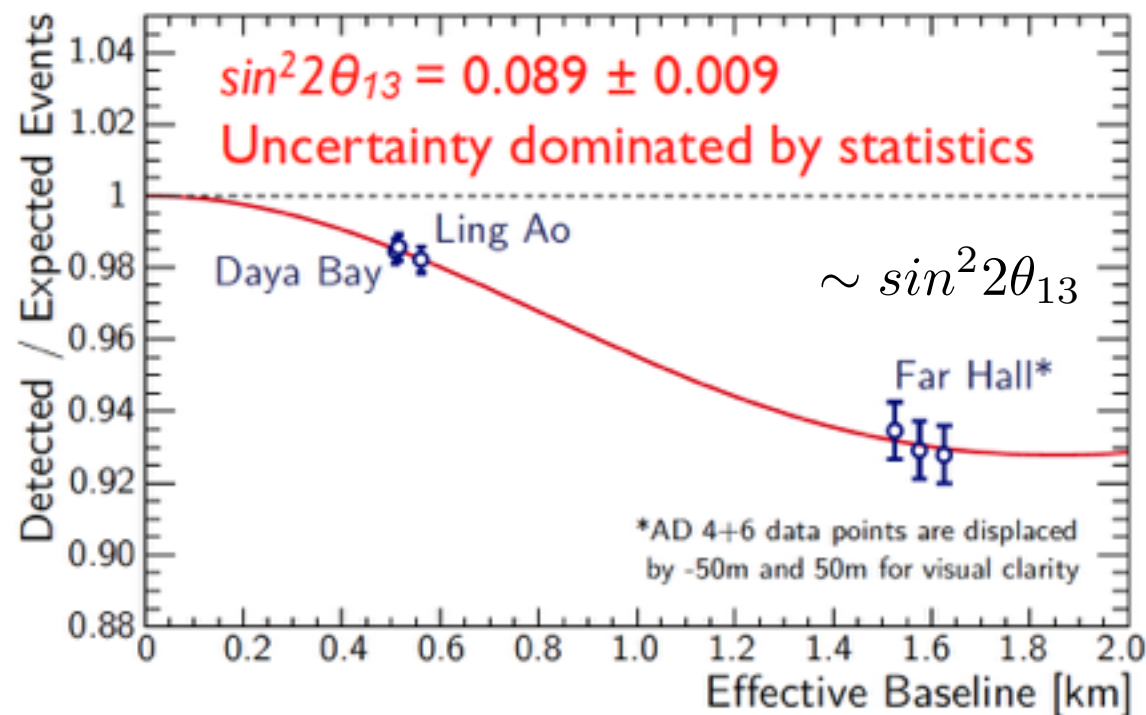
Daya Bay/DC/Reno Reactor data determines that the last element (with an unknown phase) is indeed non-zero and that the mass difference is the SAME as the one measured in the case of the ν_μ.

$$\Delta m^2 = |m_3^2 - m_{1,2}^2| \sim 2.4 \times 10^{-3}\ eV^2 \quad \sim \pi/2(3.5 MeV/1800m)/1.27$$

$$\delta m^2 = m_2^2 - m_1^2 \sim 7.5 \times 10^{-5} eV^2$$

Daya Bay Experimental Method

- **Reactors make lots of anti-electron neutrinos which are easy to detect. 2×10^{20}/sec for 1 GW**

- **Daya Bay has 6 cores each 2.9 GW → 17.4 GW total**

- **The geography is ideal with hills rising away from the bay.**

- **We have placed several detectors close to the reactors and several far away to see how many anti-electron neutrinos disappear (after accounting for the $1/r^2$ reduction.)**

- **Location is northeast of Hong Kong**

Daya Bay Antineutrino Detectors (AD)
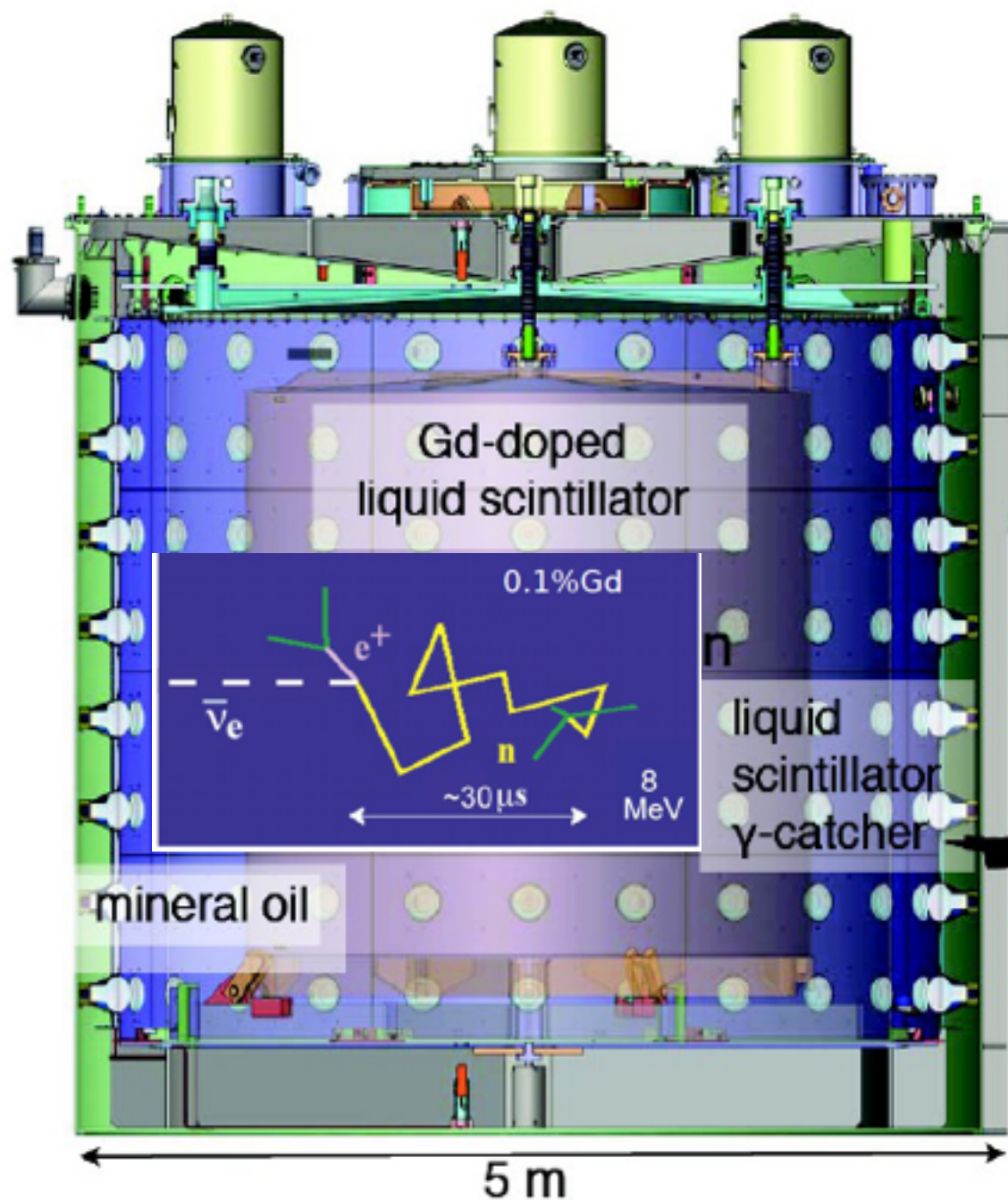
automated calibration system

reflectors at top/ bottom of cylinder

photomultipliers

steel tank

radial shield

outer acrylic tank

inner acrylic tank

Gd-doped liquid scintillator

0.1%Gd

$\overline{\nu}_e$ e^+ n ~30μs 8 MeV

n

liquid scintillator γ-catcher

mineral oil

total detector mass: ~ 110t
  inner: 20 tons Gd-doped LS (d=3m)
  mid: : 22 tons LS (d=4m)
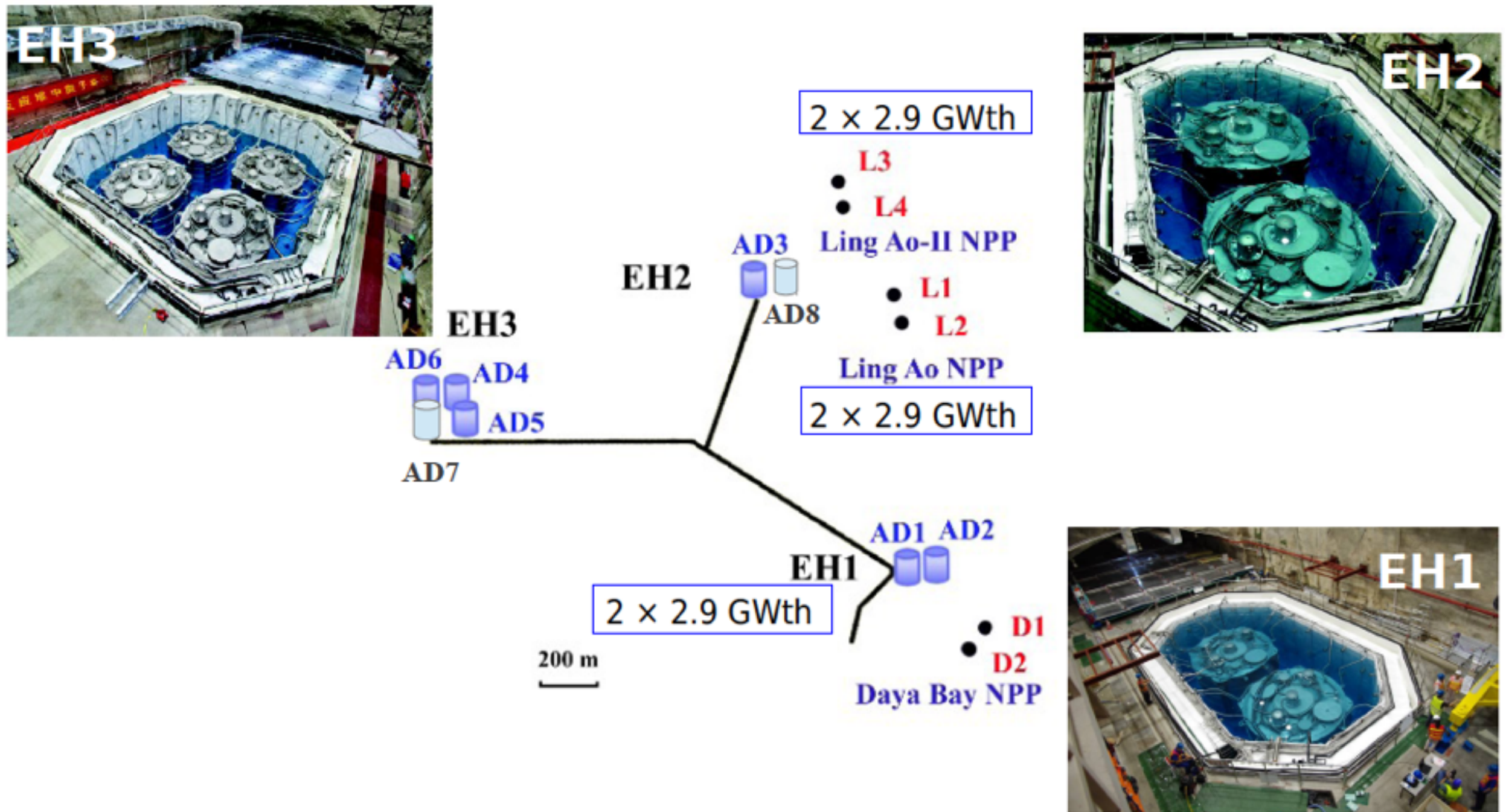 outer: 40 tons mineral oil buffer (d=5m)

photosensors: 192 8"-PMTs

5 m

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$

8 "functionally identical", 3-zone detectors reduce systematic uncertainties.

Very well defined target region

11

Completion of 8-AD Installation

EH3

EH2

EH1

2×2.9 GWth

L3
L4

Ling Ao-II NPP

L1
L2

Ling Ao NPP

2×2.9 GWth

EH2

AD3

AD8

EH3

AD6

AD4

AD5

AD7

AD1 AD2

EH1

2×2.9 GWth

D1
D2

Daya Bay NPP

200 m

Two more ADs are installed in in EH2 and EH3 in the fall of 2012.

Latest Result From Daya Bay with data up to Nov 2013.
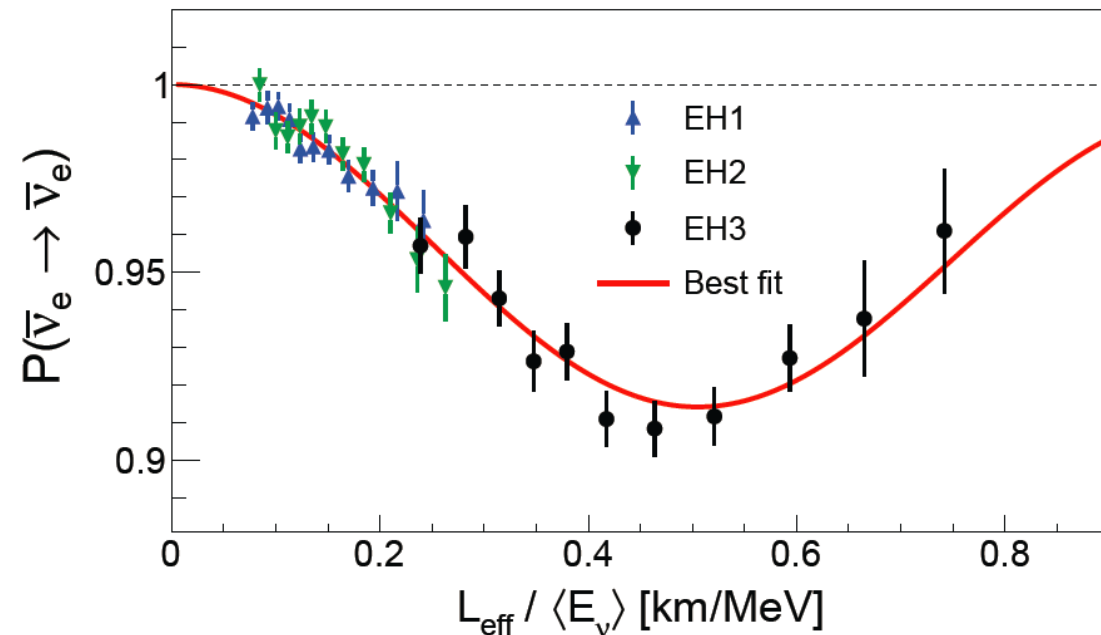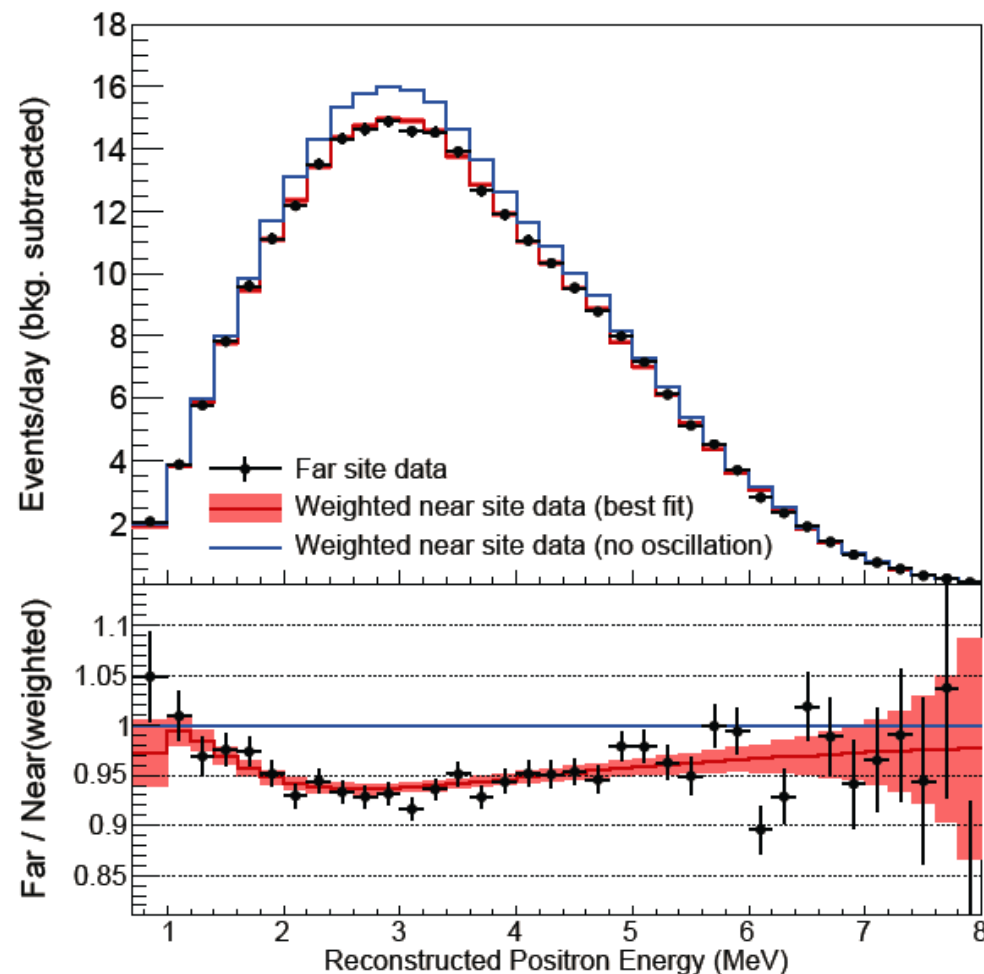
$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m_{ee}^2| = (2.42 \pm 0.11) \times 10^{-3} eV^2$$

- Using 217 days of 6 AD data and 404 days of 8 AD data.
- Total of 1.2 M events
- Improved modeling of the energy response.

nGd Spectral Analysis Result
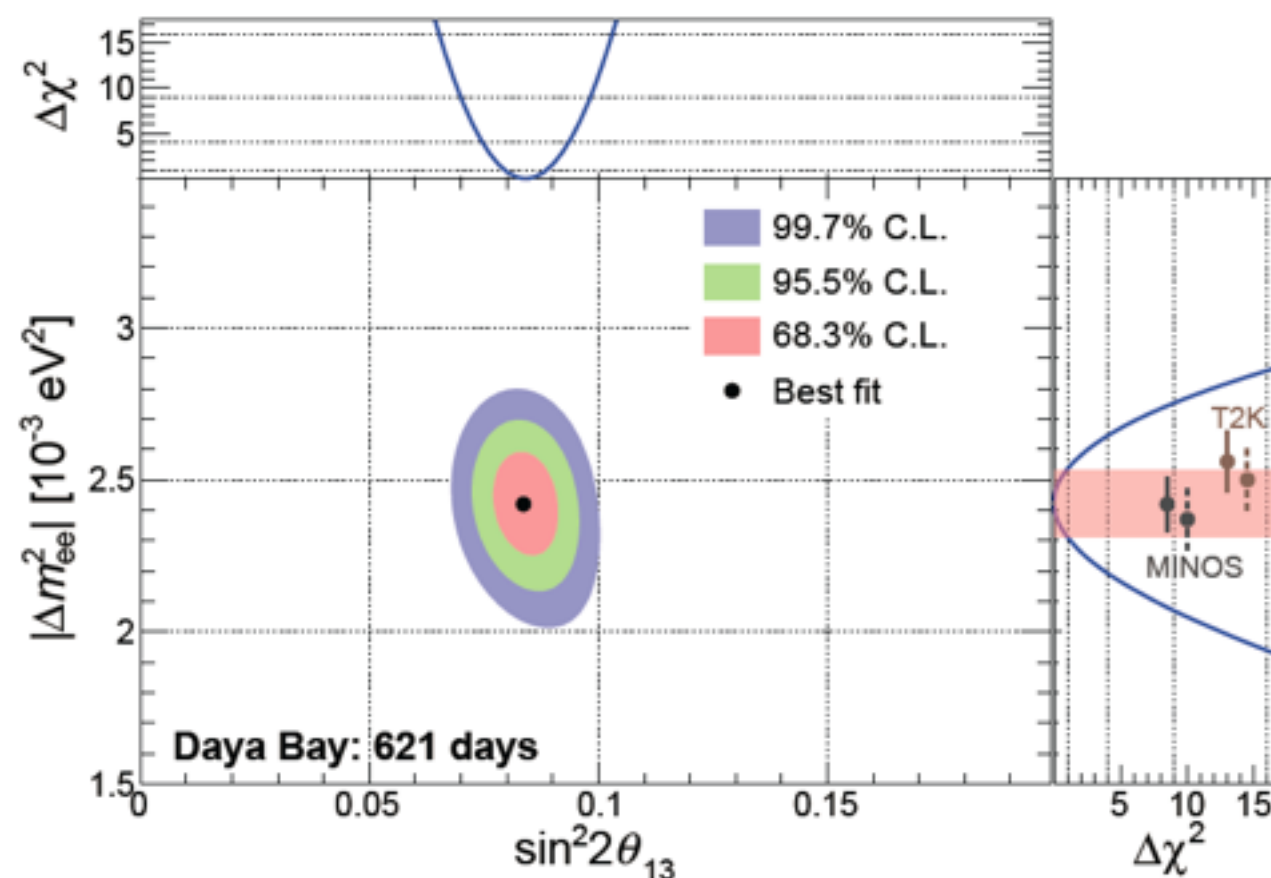
- Most presise measurement of $\sin^2 2\theta_{13}$ (6%)

- **Measurement of effective mass splitting $|\Delta m^2_{ee}|$ reaches 4%**

  ○ Consistent with muon neutrino disappearance experiments

  ○ Comparable precision

arXiv:1505.03456 [hep-ex]

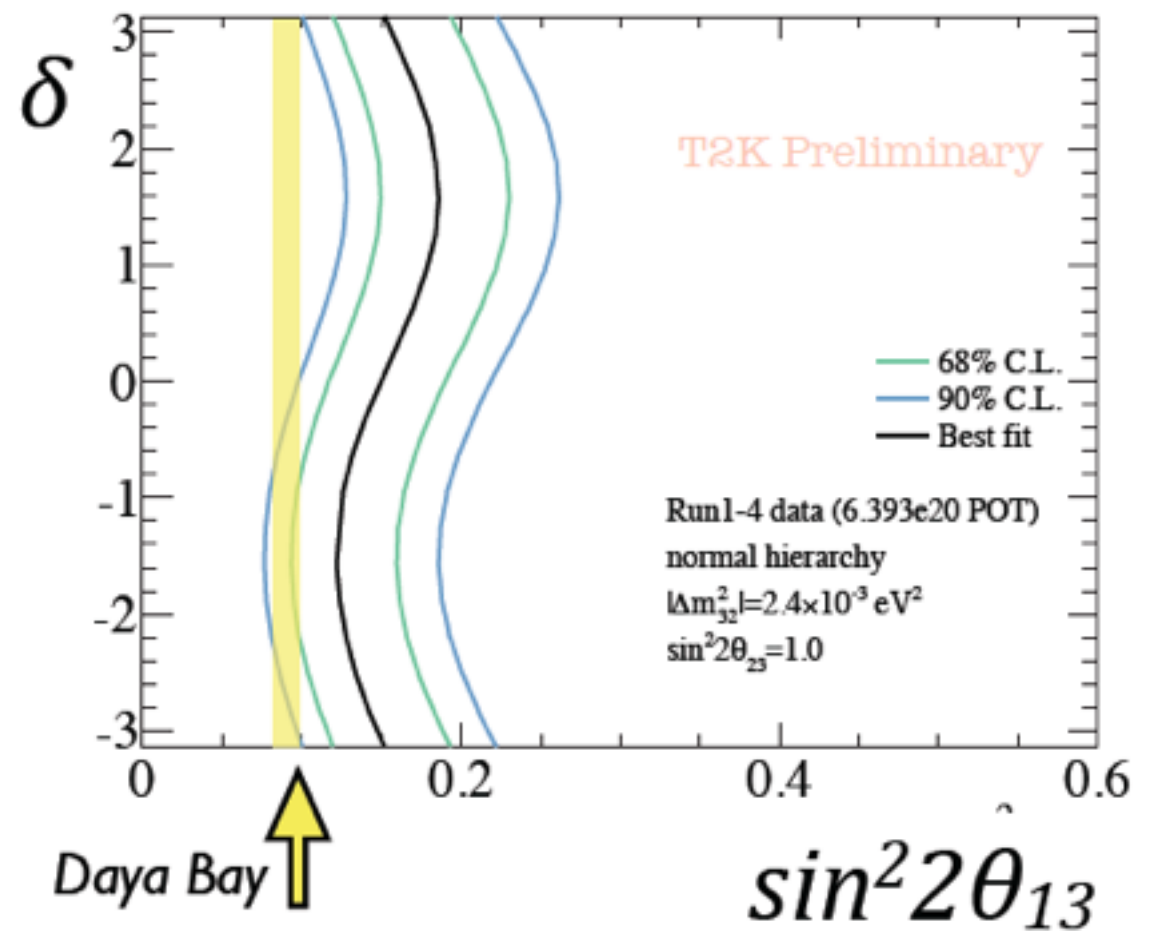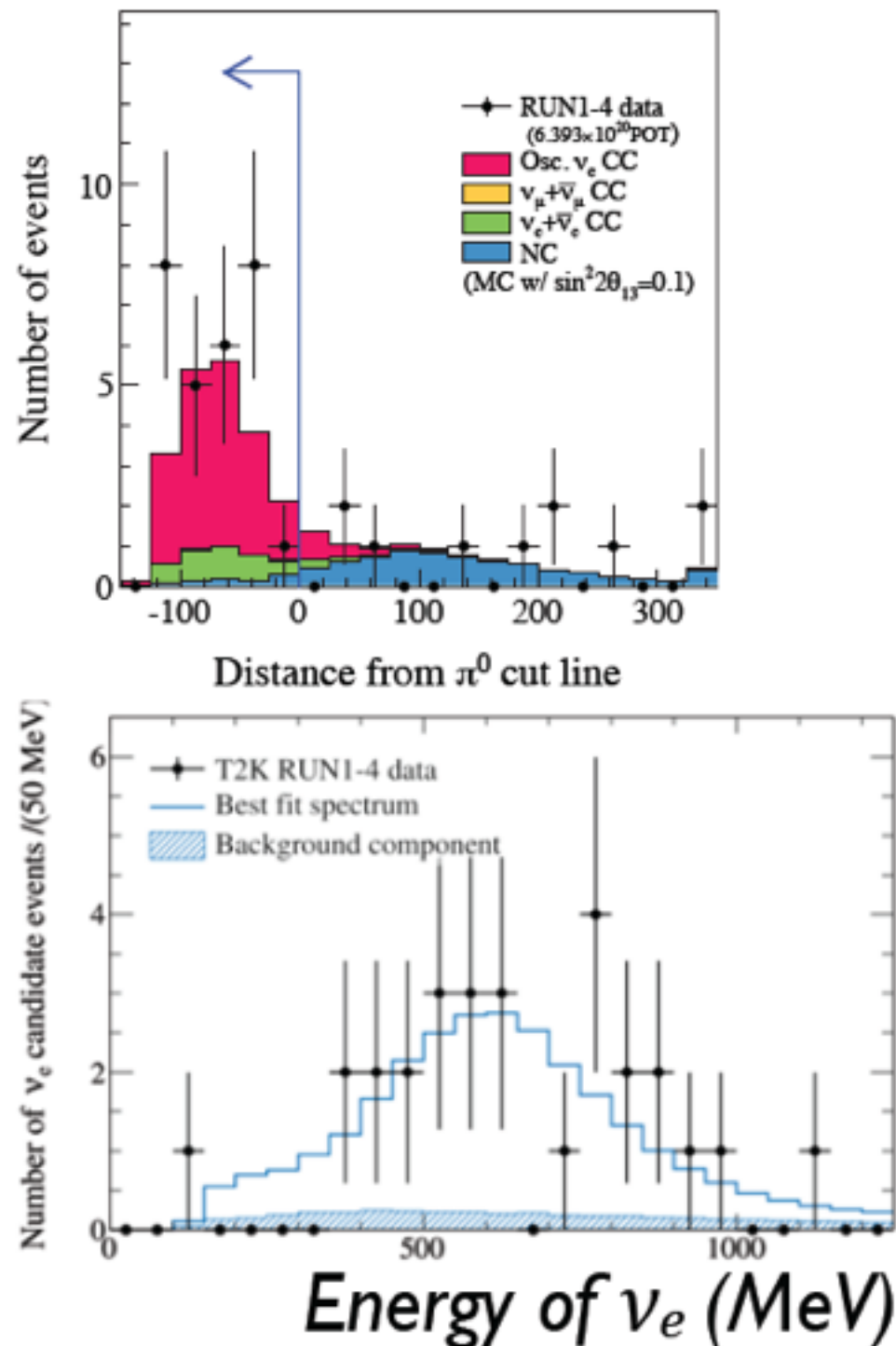$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \text{eV}^2$$

Accepted by Phys. Rev. Lett.

T2K: $\nu_\mu \to \nu_e$ Appearance

M. Wilking, EPS 2013, Stokholm
Phys. Rev. D 88, 032002 (2013)

Hints of δ≠0 ?

As of today: Oscillation of 3 massive active neutrinos is clearly the dominant effect:

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$

For 3 Active neutrinos.

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata matrix

(Double β decay only)

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

Atmospheric, Accel. | **CP Violating Phase** | **Reactor, Accel.** | **Solar, Reactor** | **Majorana CP Phases**

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

Range defined for Δm_{12}, Δm_{23}

For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

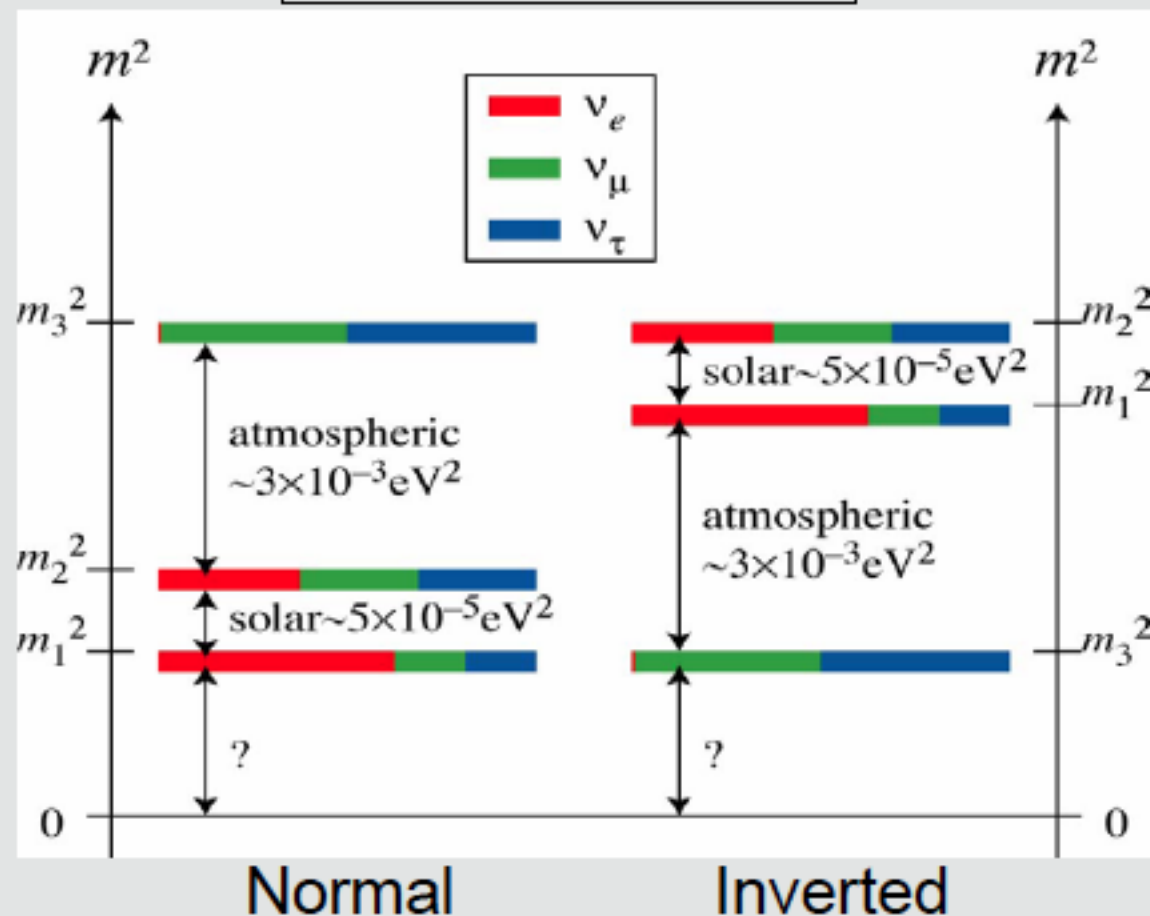$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 (1.27\frac{\Delta m^2 L}{E})$$

CP Violating Phases: implication for Antimatter/Matter asymmetry via Leptogenesis?

SUMMARY OF RESULTS FOR THREE ACTIVE ν TYPES

$\Delta m \sim 0.05$ eV

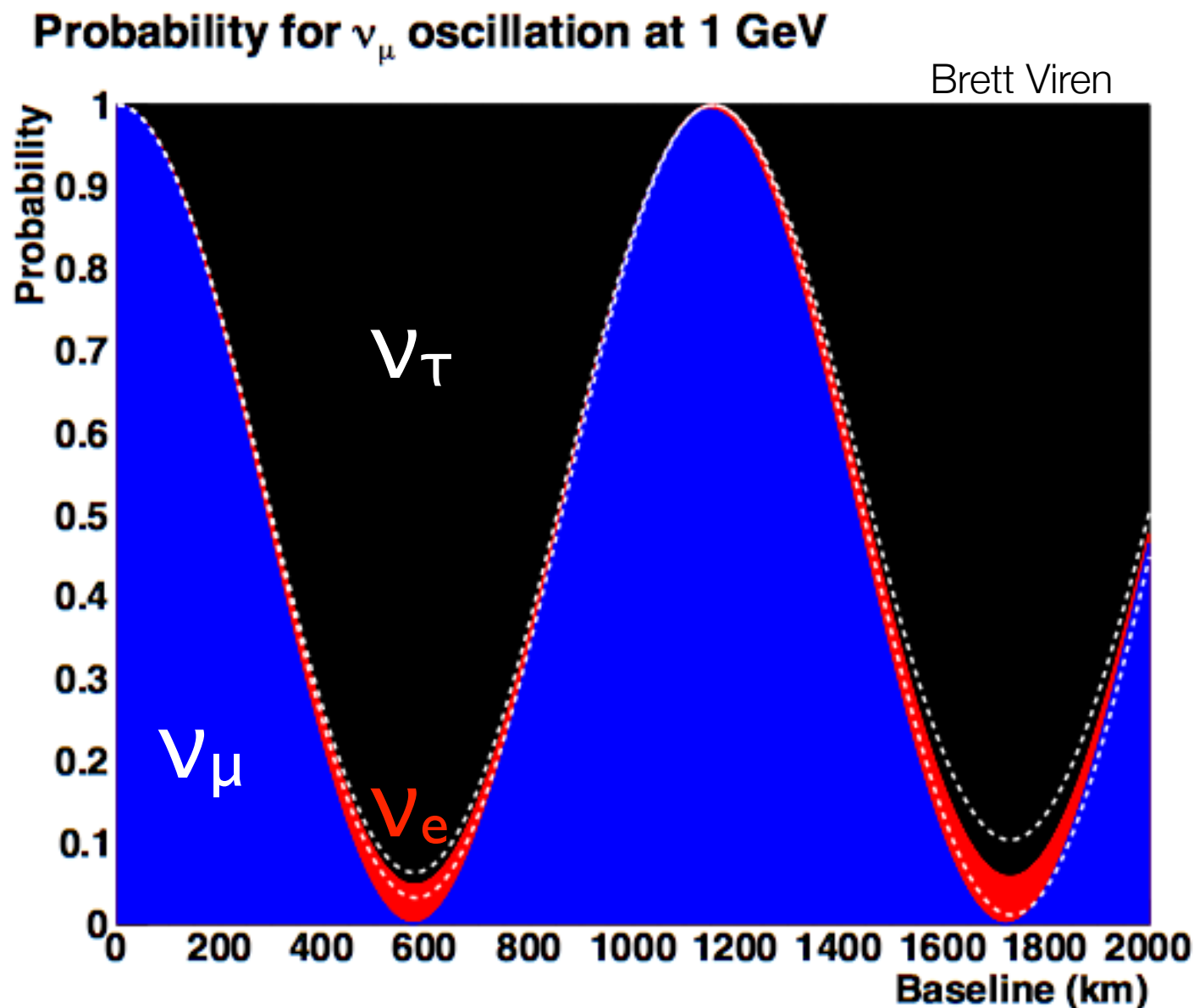| Parameter	best-fit ($\pm 1\sigma$)
$\Delta m_\odot^2 \, [10^{-5} \text{ eV}^2]$	$7.58^{+0.22}_{-0.26}$
$|\Delta m_A^2| \, [10^{-3} \text{ eV}^2]$	$2.35^{+0.12}_{-0.09}$
$\sin^2 \theta_{12}$	$0.306 \, (0.312)^{+0.018}_{-0.015}$
$\sin^2 \theta_{23}$	$0.42^{+0.08}_{-0.03}$
$\sin^2 \theta_{13} \, [140]$	$0.021 \, (0.025)^{+0.007}_{-0.008}$
$\sin^2 \theta_{13} \, [142]$	0.0251 ± 0.0034

Mass Hierarchies

**No strong theoretical motivation for choosing between these hierarchies**

Hierarchy, CP phase, and precise values of mixings could be very important to gain understanding of underlying symmetries. See talk by Smirnov from recent meeting.

The full picture of the oscillation effect starting with pure muon type neutrino.

Probability for ν_μ oscillation at 1 GeV

Brett Viren

Probability (y-axis): 1, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 0

ν_τ

ν_μ

ν_e

Baseline (km): 0, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000

Dashed white lines correspond to CP violation or the unknown phase.

**Notice that for sizable effects one needs long distances and large energies.**
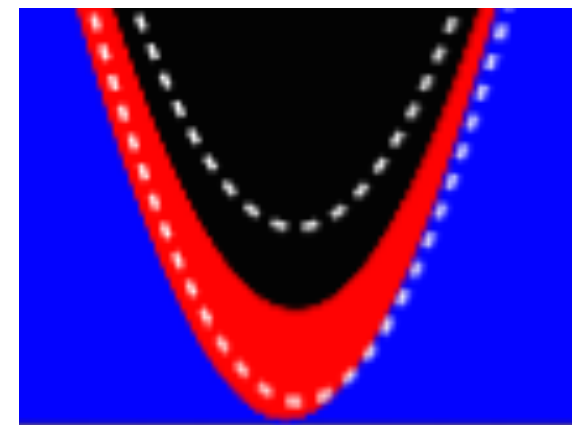
- **There are precise predictions:**
  - **Large Matter Effects (not yet seen in a laboratory experiment)**
  - **Potentially large CP violation (not yet seen)**
  - **We should measure this picture with a detailed spectrum. We need to measure electron and muon type of neutrinos at high energies.**

Importance of neutrino mass

Left   Z

Right if $V_Z > -p/E$

Z

In a moving frame with V_Z
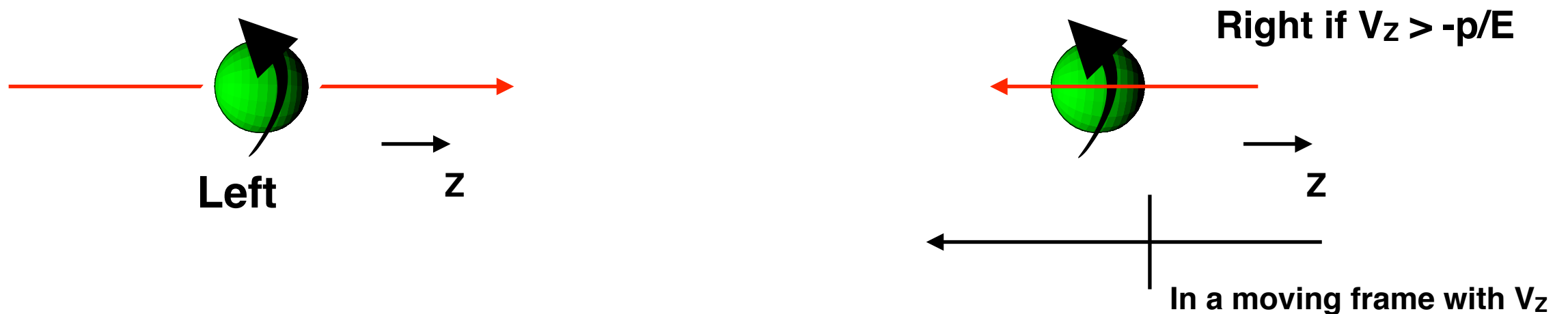
- In the standard model only ν_L interacts with matter, ν_R does not interact. Since neutrinos are produced in weak interactions only, ν_R do not exist.

- Handedness and Helicity are identical if particles are massless.

- Particles with mass can be transformed to opposite helicity by a Lorentz transformation.

- **Since massive neutrinos have no charge, is anti-$\nu_L == \nu_R$?** This would simplify our understanding and also lead to Lepton-Number violation.

0-neutrino double beta decay
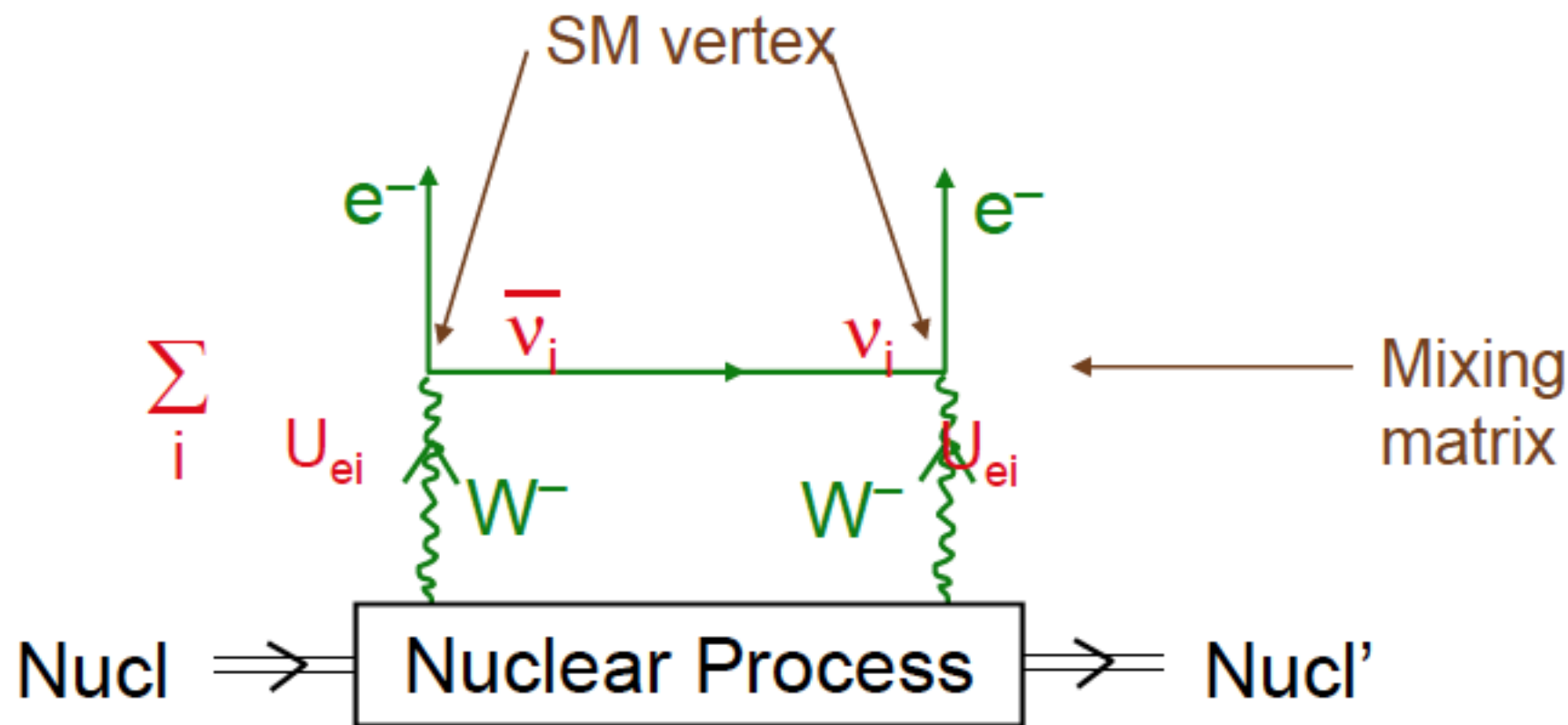
- Only practical way to test for Majorana (are neutrinos their own anti-particles ?) nature.

- Amplitude must be $\propto (G_F)^2$ therefore rate will be very small compared to ordinary beta decay which has amplitude of G_F.

- In the decay a right-handed antineutrino is emitted and then a left-handed neutrino is absorbed. The RH neutrino has a LH projection only if it has a small mass $\Rightarrow$ Amplitude must be $\propto m_\nu/E$

- Therefore 0nuDBB is sensitive to Majorana neutrino mass.
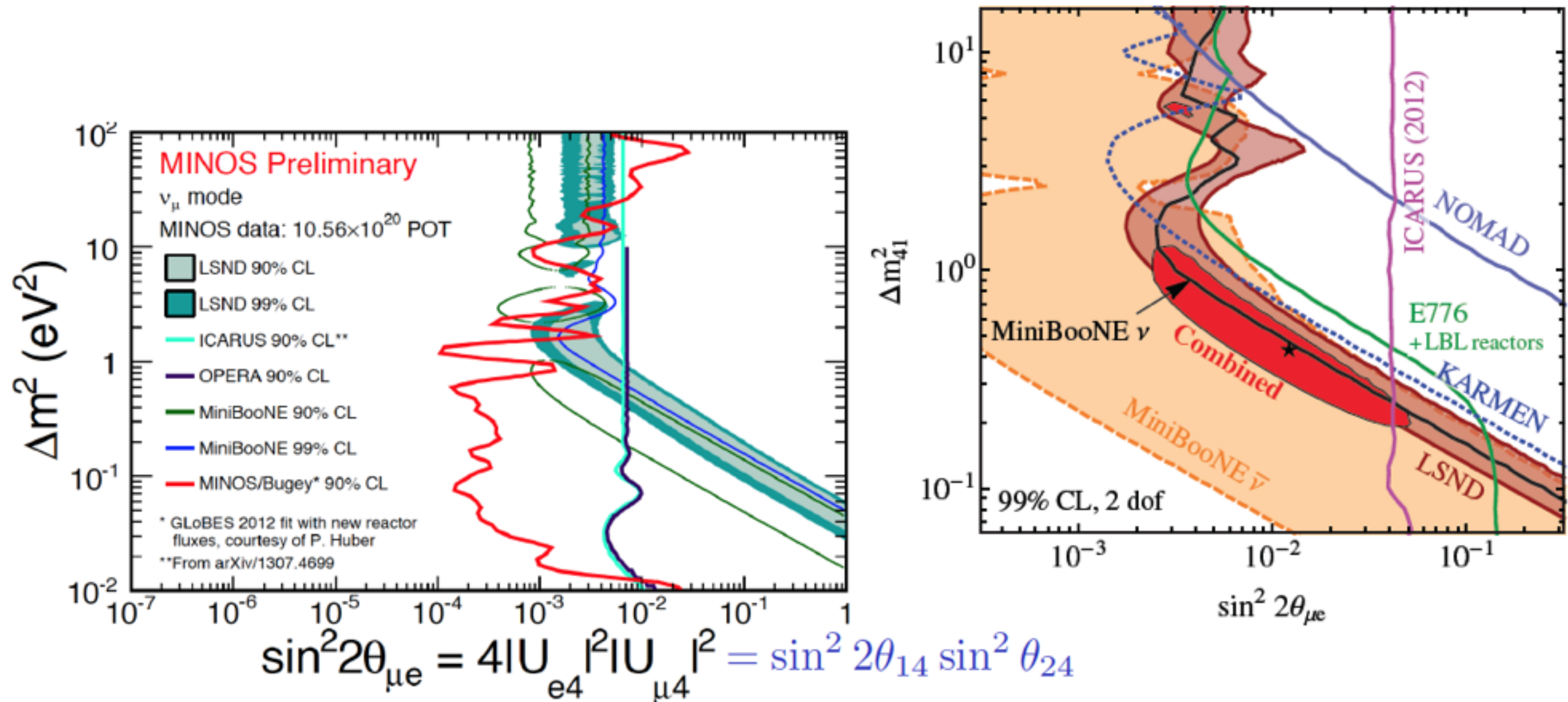
Experimental double beta decay
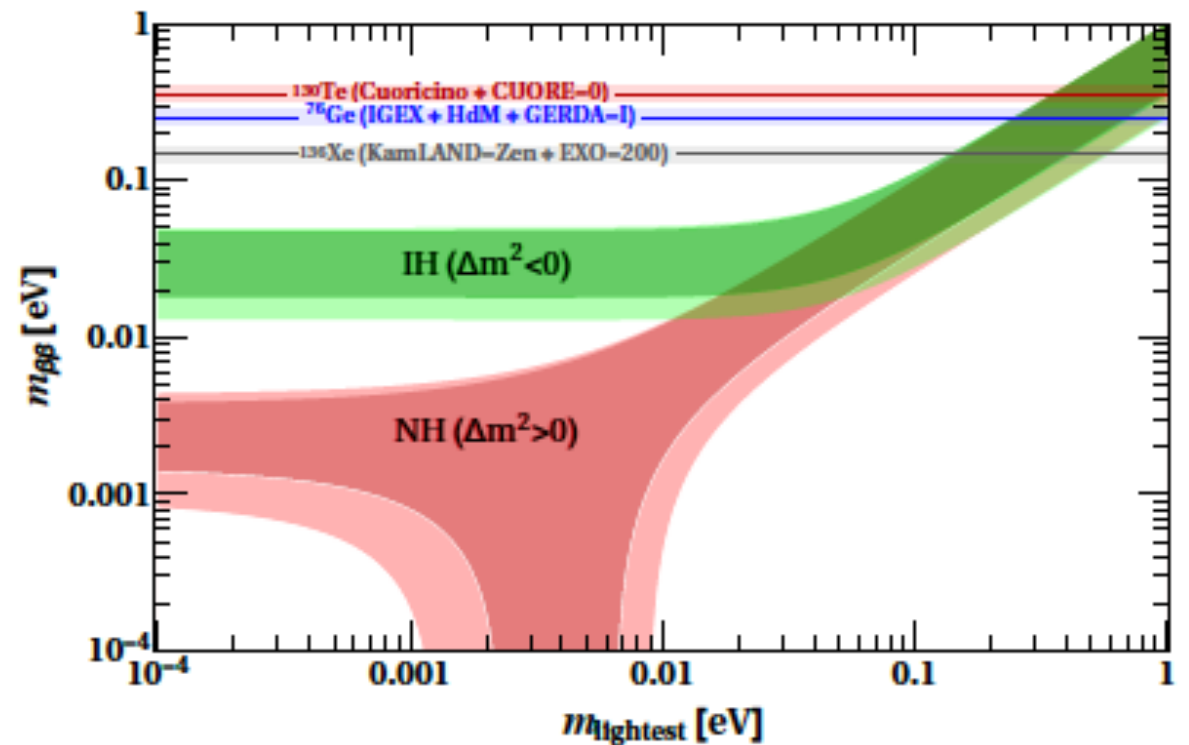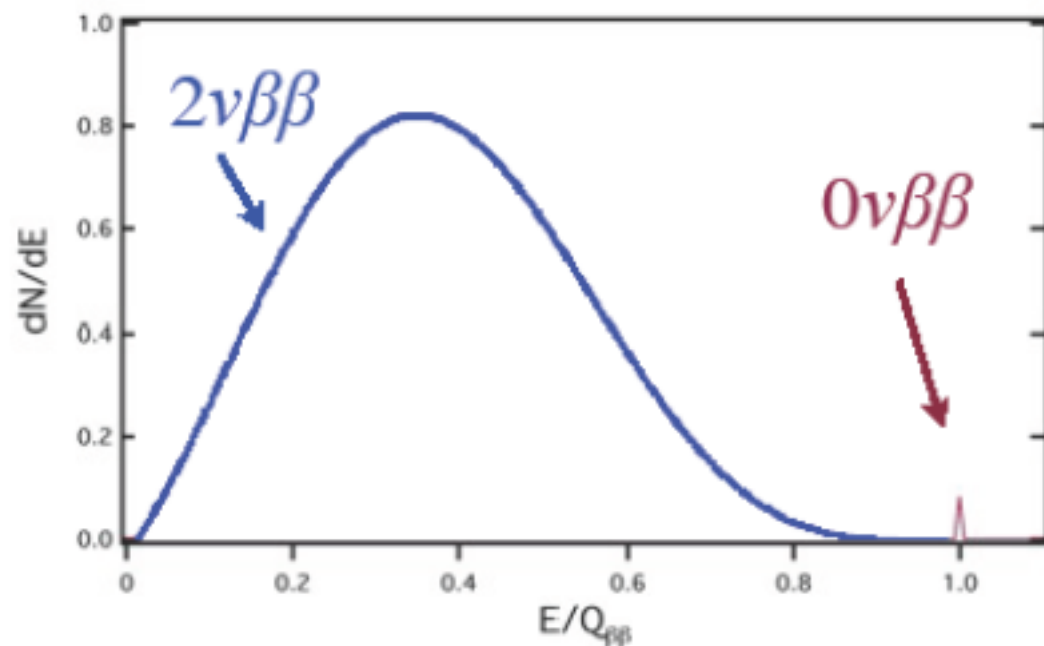
$$\langle m_{\beta\beta} \rangle = \sum_{i=1,2,3} U_{ei}^2 m_i$$

$$\Gamma^{0\nu} = 1/T_{1/2}^{0\nu} \propto G_F^4 \frac{|m_{\beta\beta}|^2}{m_e^2} \times (factors)$$

- Must test in nuclei where single beta decay not allowed.

- (A,Z) →(A,Z+2) + 2 e⁻ + 2 (anti-nu) ΔL = 0

- (A,Z) →(A,Z+2) + 2 e⁻   ΔL = 2

- Lifetimes of >10^{26} years must be measured (with >tons of nuclei) to reach sensitivity indicated by oscillation physics.

Anomalies

- There are indications of anomalies around ~1 eV.

- These are getting severely limited by disappearance results.

Implications of the large θ₁₃

- **It should be possible to see effects of matter enhancement with atmospheric neutrinos and determine the mass hierarchy => INO (India)**

- **It should be possible to see oscillatory signal in reactor neutrinos and determine the mass hierarchy => JUNO (China), RENO50 (Korea), etc.**

- **Best possibility: An accelerator based program to get enough statistics to perform a comprehensive experiment with** $\nu_\mu \rightarrow \nu_e$

Conclusion

- There is an exciting new scientific opportunity due to the discovery that the neutrino is a superposition of 3 mass states. We do not know all the implications of this.

- We can now measure if neutrinos violate the CP symmetry. This is an extremely important measurement that is guaranteed !

- In the next lecture I will explore how such a measurement can be done and the technologies needed.